Status and Prospects for SUSY @ 7 TeV

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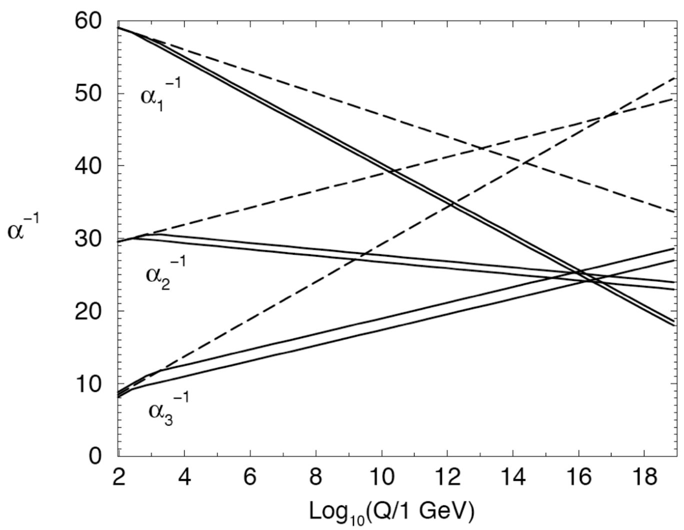
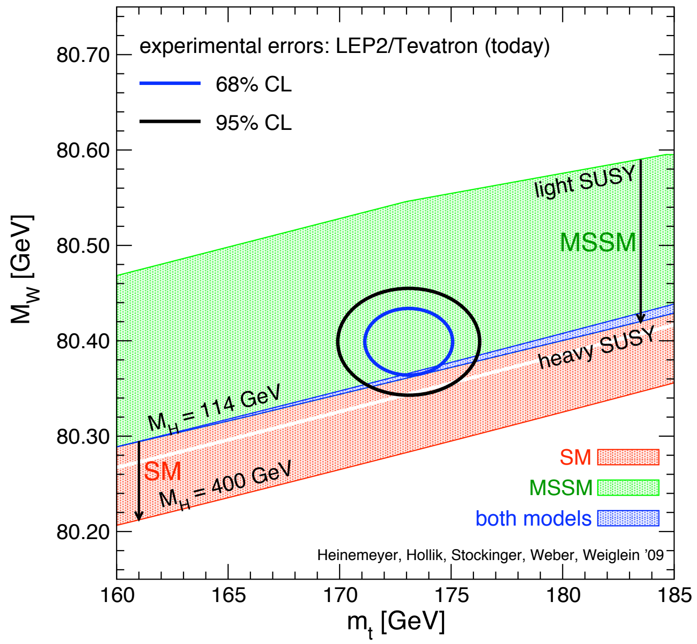
CEA, Saclay, 1 April 2010

Why SUSY?

- Symmetry between fermions and bosons, providing a unified description of matter, gauge and Higgs fields.
- Unique extension of relativistic space-time symmetries.
- Solves the gauge hierarchy problem.
- Predicts a light Higgs.
- Allows for gauge coupling unification → GUT?
- Excellent fit to precision electroweak data.
- Provides cold dark matter candidate
- Arguably the best motivated extension of the SM

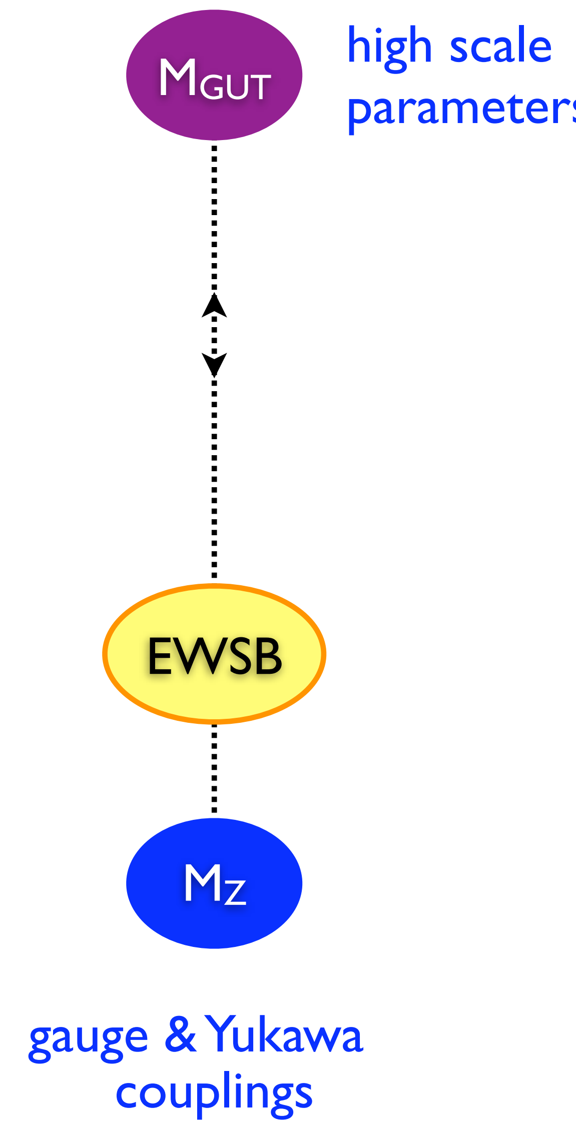




MSSM

Minimal supersymmetric standard model

particle	spin	superpartner	spin
quarks	$1/2$	squarks	0
leptons	$1/2$	sleptons	0
gauge bosons	1	gauginos	$1/2$
Higgs bosons	0	higgsinos	$1/2$
graviton	2	gravitino	$3/2$



full MSSM: ~100 free parameters (soft breaking terms)

CMSSM (mSUGRA): $m_{1/2}$, m_0, A_0, $\tan\beta$, sign μ.

NUHM: $m_{1/2}$, m_0, $m_{H_{1,2}}$, A_0, $\tan\beta$, sign μ.

NUHM-1: $m_{H_1} = m_{H_2}$, NUHM-2: $m_{H_1} \neq m_{H_2}$

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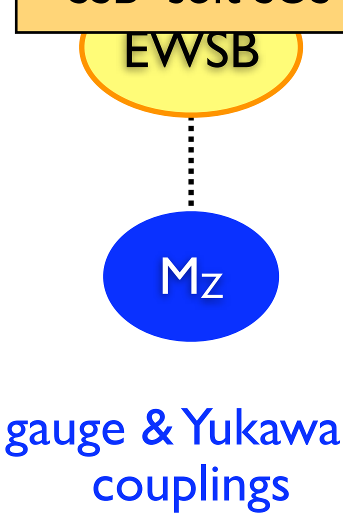
Disclaimer:
There's been a lot of work recently regarding low-scale SSB*, SSB from extra dimensions, string-inspired models, non-universal / non-minimal models, higgsless SUSY, etc, etc. These will not be discussed here.

* SSB=soft SUSY breaking



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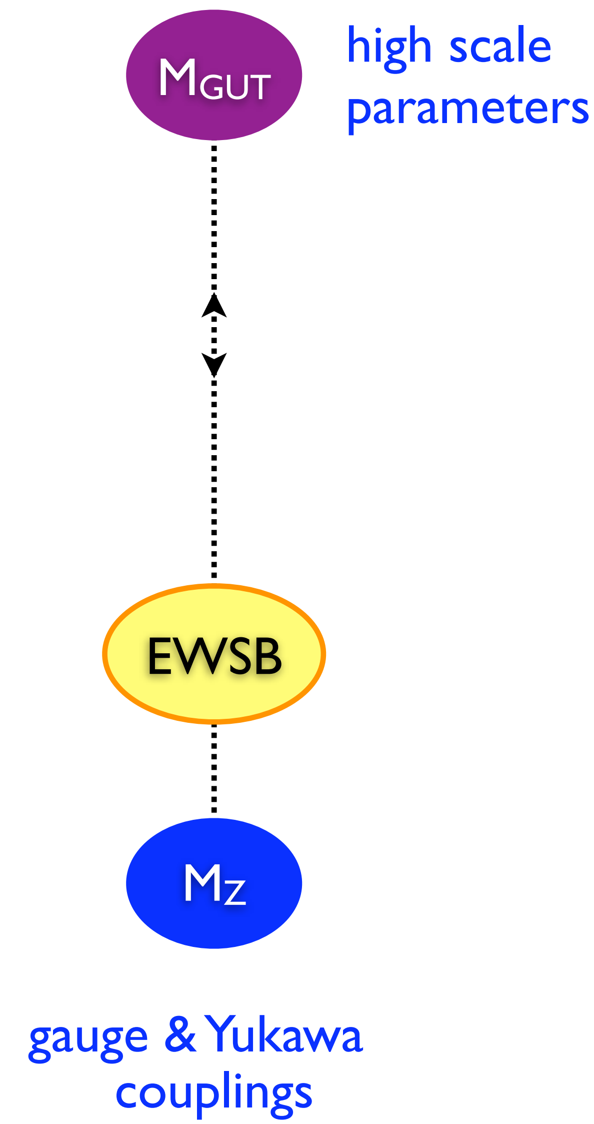

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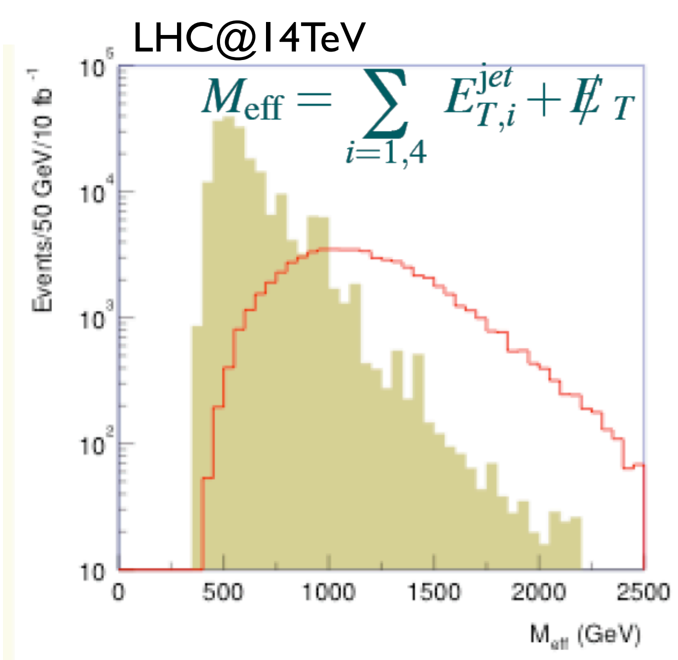
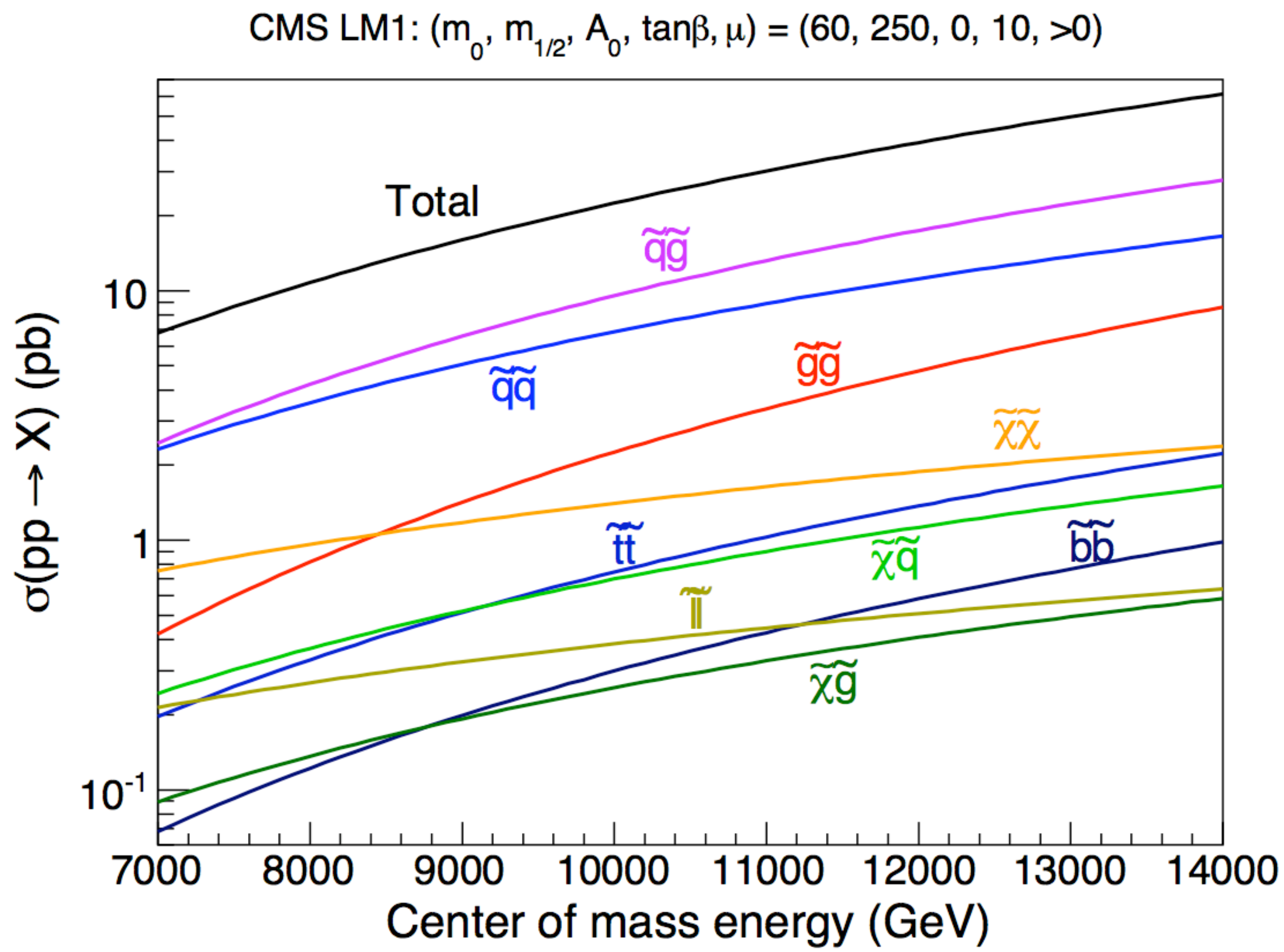
SUSY at LHC

- General expectation at LHC: large Xsections for squarks and/or gluinos. Strong interaction + the power of phase-space.
- Once produced, squarks/gluinos will decay into lighter sparticles until the LSP* is reached
  - ➡ cascade decays
  - ➡ high-p_T jets
  - ➡ large missing E_T





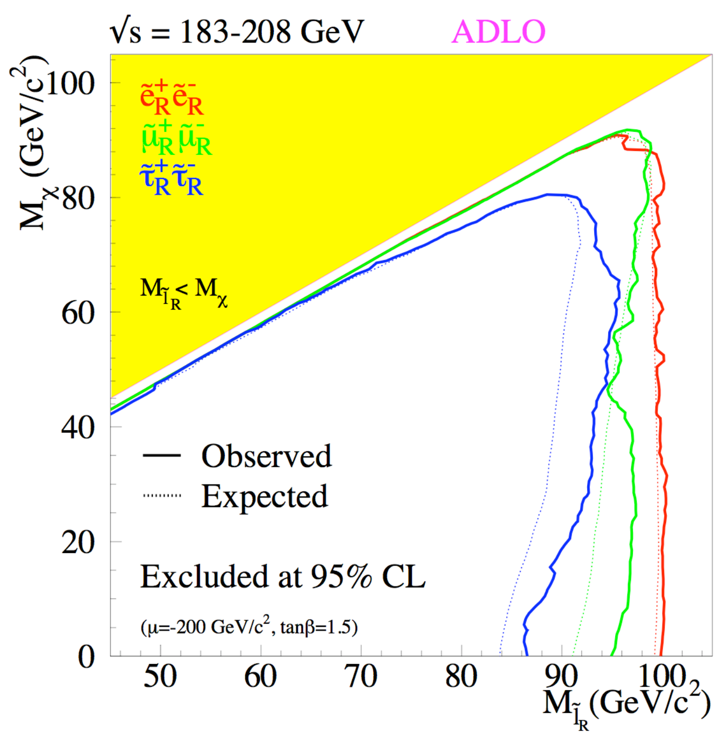
courtesy S. Sekmen

*) LSP = lightest SUSY particle, stable if R-parity is conserved

Limits and constraints

So far only lower mass limits and indirect constraints, e.g.,

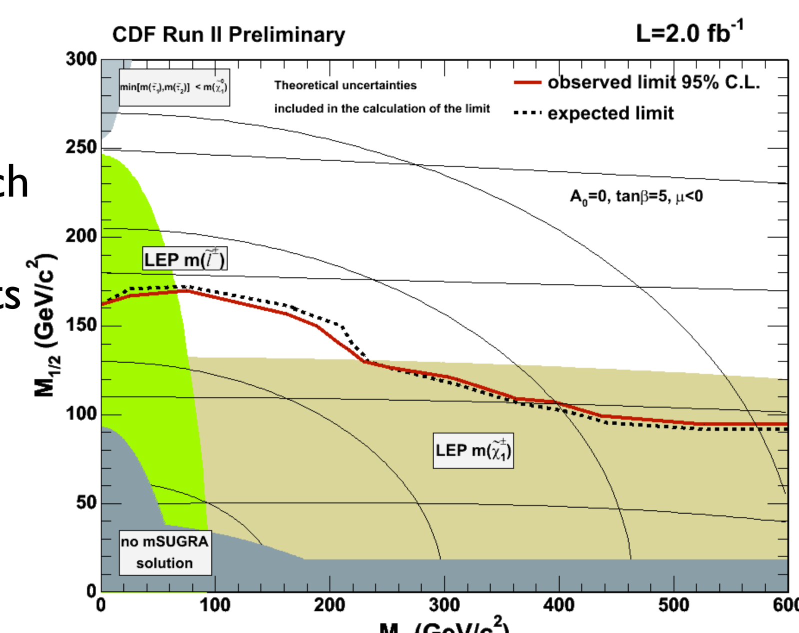
LEP: charged sparticle $M \gtrsim 100$ GeV

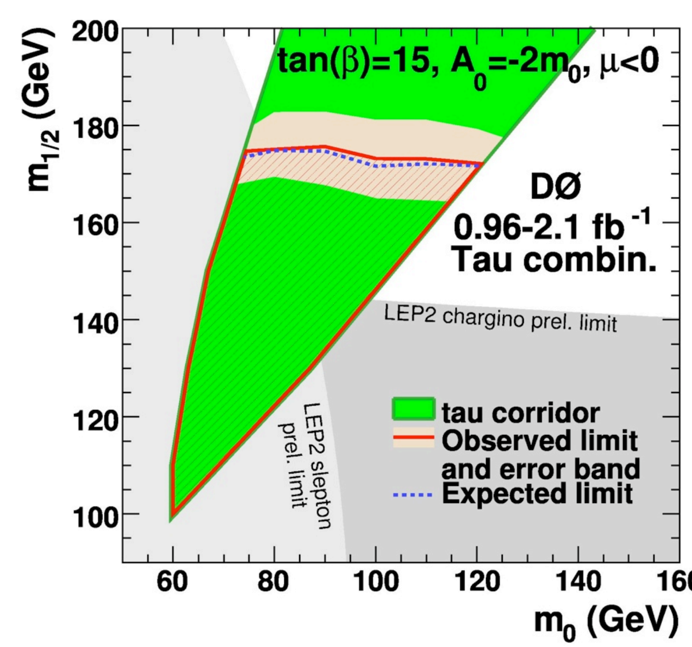


$BR^{exp}_{b\to s\gamma}/BR^{SM}_{b\to s\gamma}$	$1.117 \pm 0.076_{exp} \pm 0.082_{th(SM)}$
$BR(B_s \to \mu^+\mu^-)$	$< 4.7 \times 10^{-8}$
$BR^{exp}_{B\to\tau\nu}/BR^{SM}_{B\to\tau\nu}$	$1.25 \pm 0.40_{[exp+th]}$
$BR(B_d \to \mu^+\mu^-)$	$< 2.3 \times 10^{-8}$
$BR^{exp}_{B\to X_s\ell\ell}/BR^{SM}_{B\to X_s\ell\ell}$	0.99 ± 0.32
$BR^{exp}_{K\to\mu\nu}/BR^{SM}_{K\to\mu\nu}$	$1.008 \pm 0.014_{[exp+th]}$
$BR^{exp}_{K\to\pi\nu\bar{\nu}}/BR^{SM}_{K\to\pi\nu\bar{\nu}}$	< 4.5
$\Delta M^{exp}_{B_s}/\Delta M^{SM}_{B_s}$	$0.97 \pm 0.01_{exp} \pm 0.27_{th(SM)}$
$\frac{(\Delta M^{exp}_{B_s}/\Delta M^{SM}_{B_s})}{(\Delta M^{exp}_{B_d}/\Delta M^{SM}_{B_d})}$	$1.00 \pm 0.01_{exp} \pm 0.13_{th(SM)}$
$\Delta\epsilon^{exp}_K/\Delta\epsilon^{SM}_K$	$1.08 \pm 0.14_{[exp+th]}$
$a^{exp}_\mu - a^{SM}_\mu$	$(30.2 \pm 8.8) \times 10^{-10}$
M_h [GeV]	> 114.4 (see text)
$\Omega_{CDM}h^2$	0.1099 ± 0.0062

B-physics!

Tevatron: begins to reach beyond LEP but mass limits quite model dependent





→ severe constraints on parameter space

Fits: Bayesian

Allanach, Lester,
AbdusSalam et al,
Baltz, Gondolo,
Belanger et al,
Roszkowski et al,

- Markov Chain Monte Carlo (MCMC) or MultiNest sampling.
- Marginalized posterior PDFs (probability density functions) for parameter inference.

likelihood prior

posterior

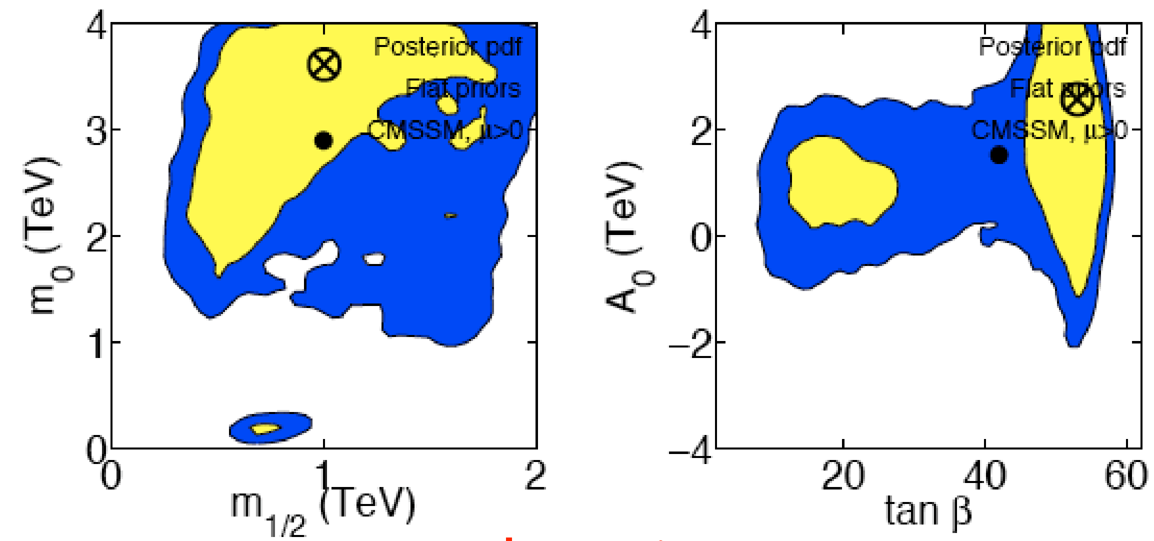
$$p(m|d) = \frac{p(d|\xi)\pi(m)}{p(d)}$$

evidence

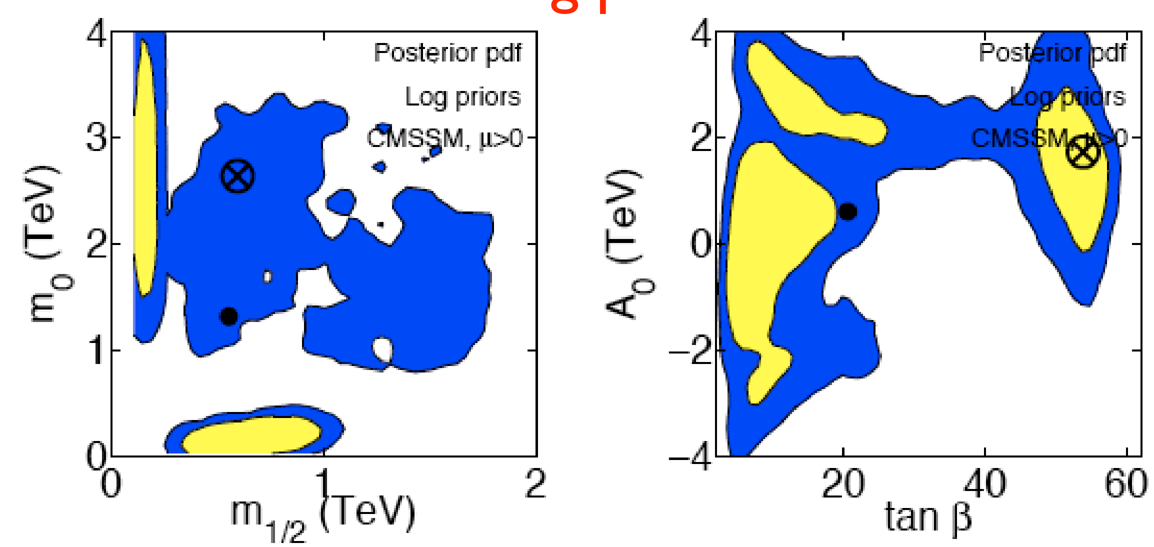
- Alternative: profile likelihoods, but more difficult to evaluate.
- Prior dependence!!

PHYS+NUIS+COLL
+CDM+BSG

linear prior



log prior



Trotta et al, arXiv:0809.3792

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posterior, likelihood, prior, evidence:

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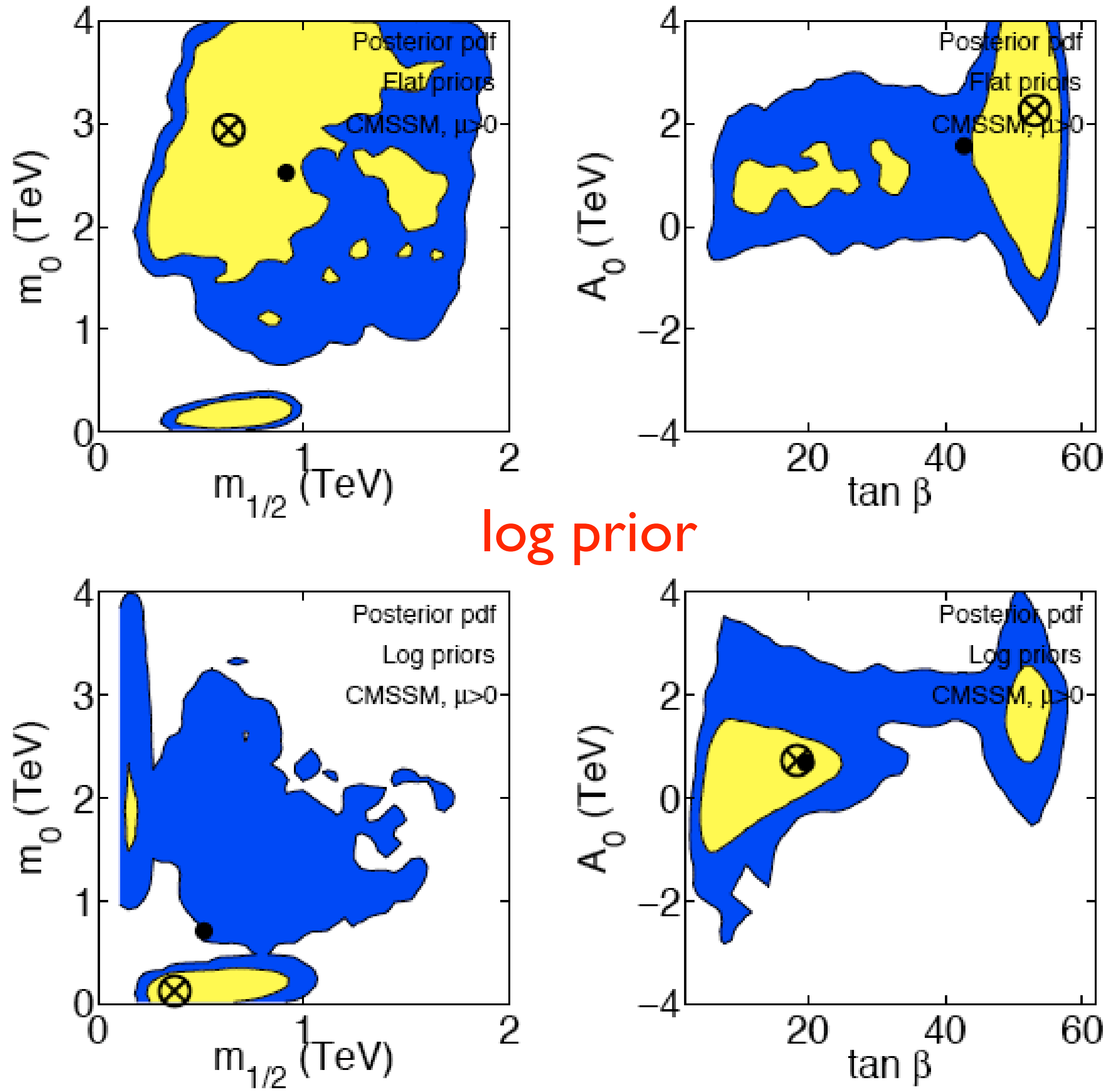
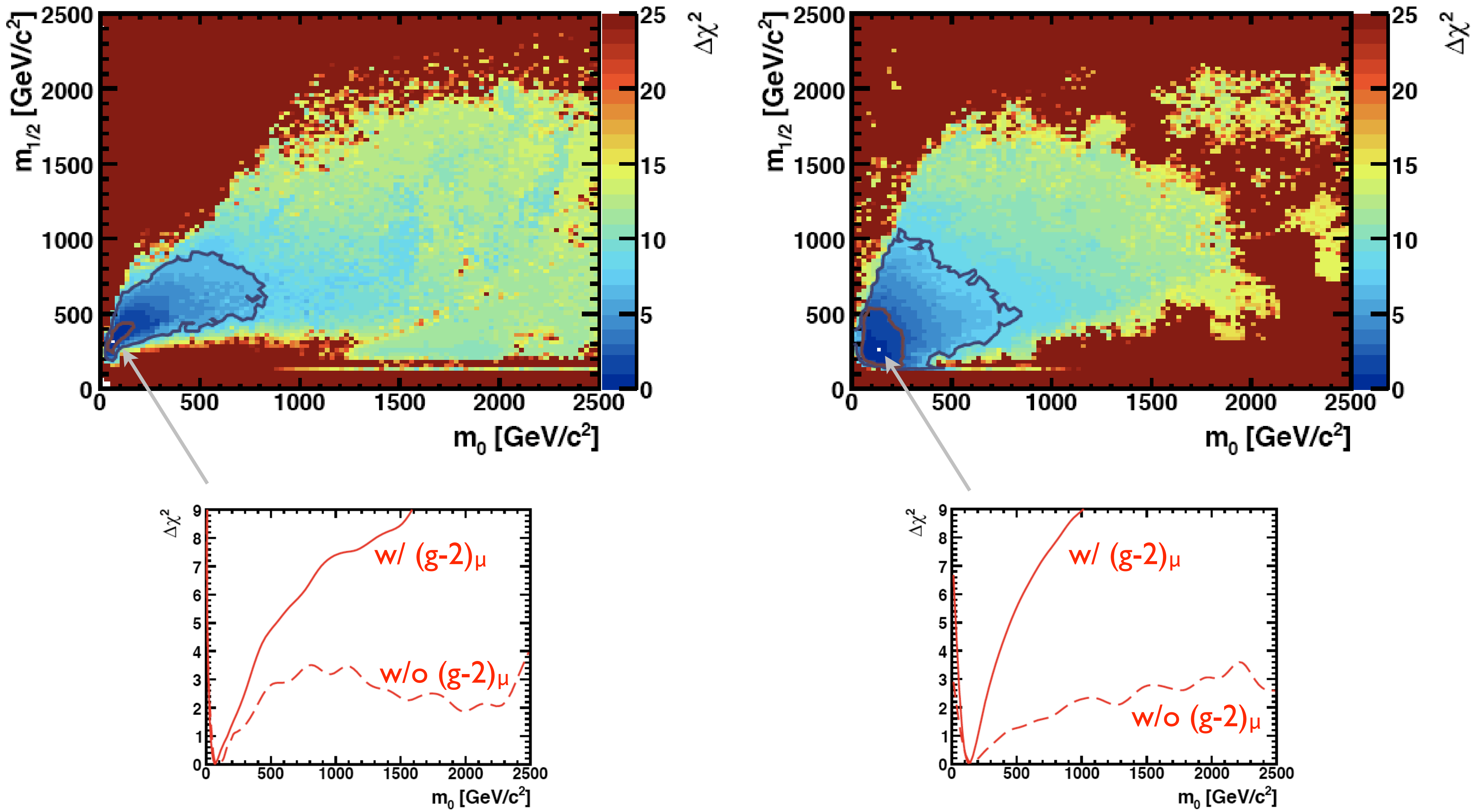


Trotta et al, arXiv:0809.3792

O. Buchmüller et al, arXiv:0907.5568
("Mastercode")

Fits: Frequentist

CMSSM NUHM-1



Best fit at $m_{\tilde{g}} \approx 750/600$ GeV, $\tan\beta \approx 11$.

O. Buchmüller et al, arXiv:0907.5568 ("Mastercode")

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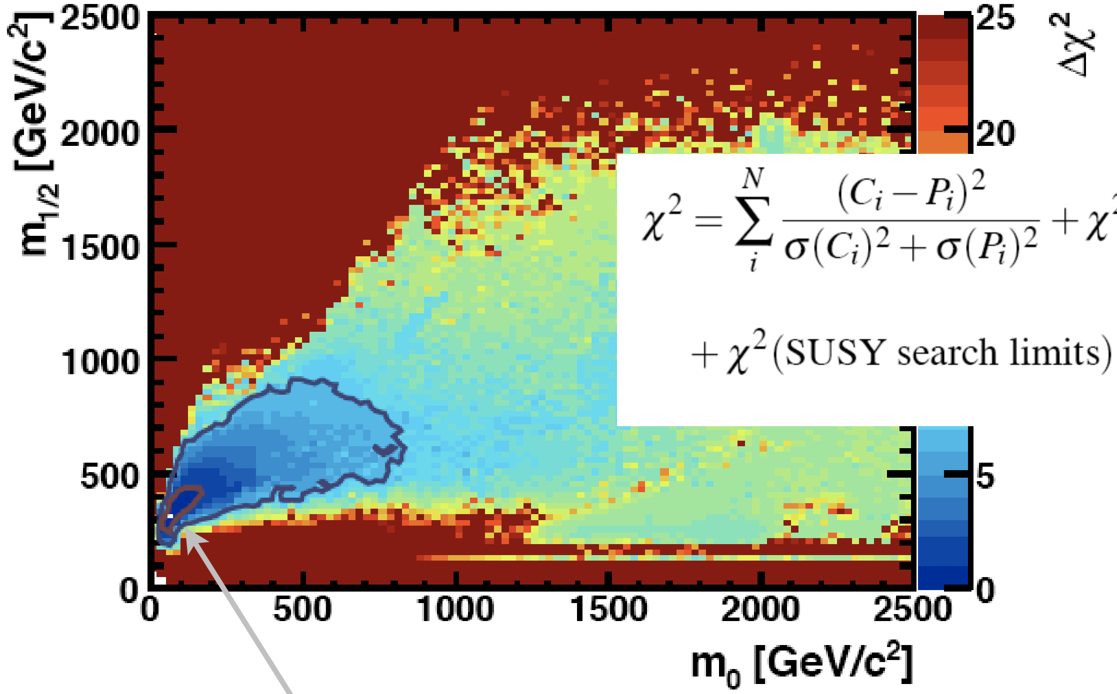
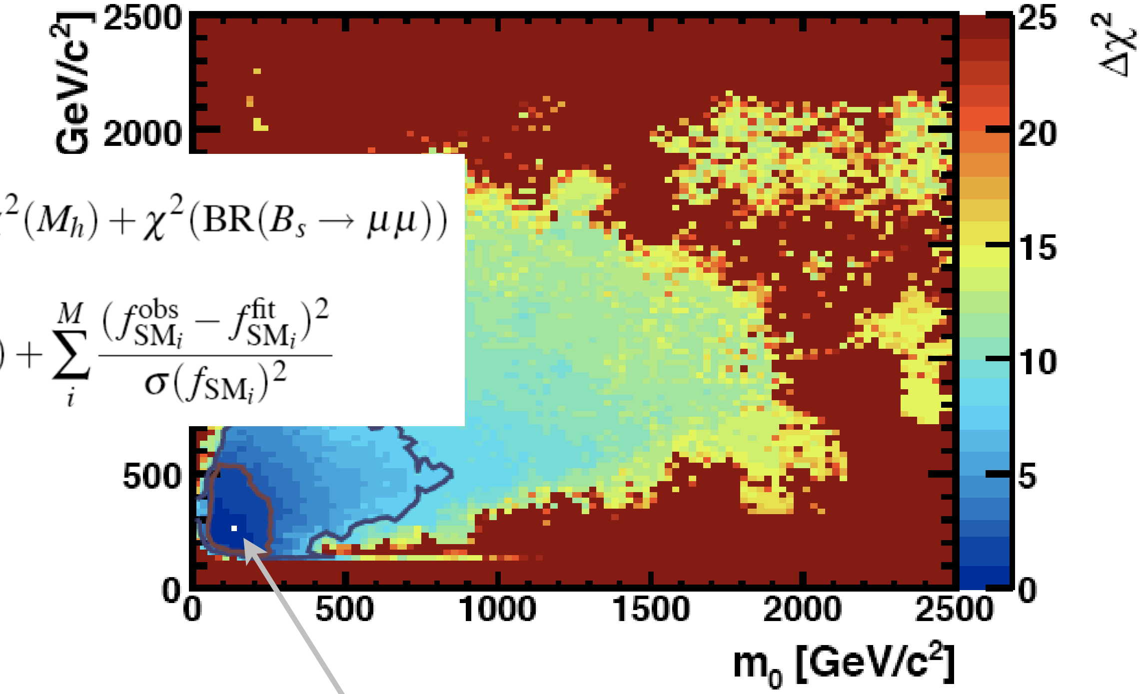
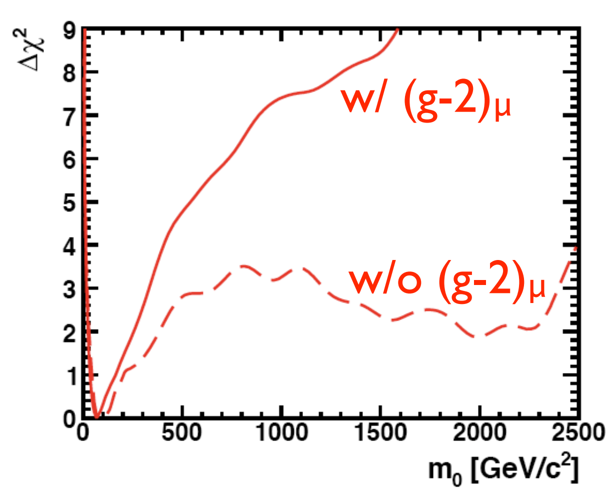


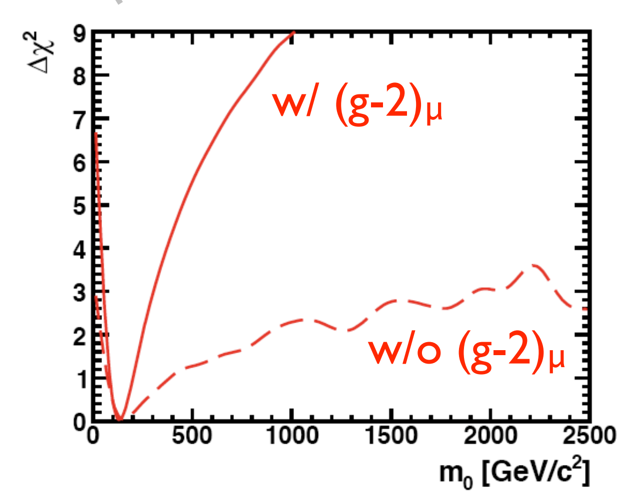
NUHM-1



$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$

$$+ \chi^2(\text{SUSY search limits}) + \sum_i^M \frac{(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$





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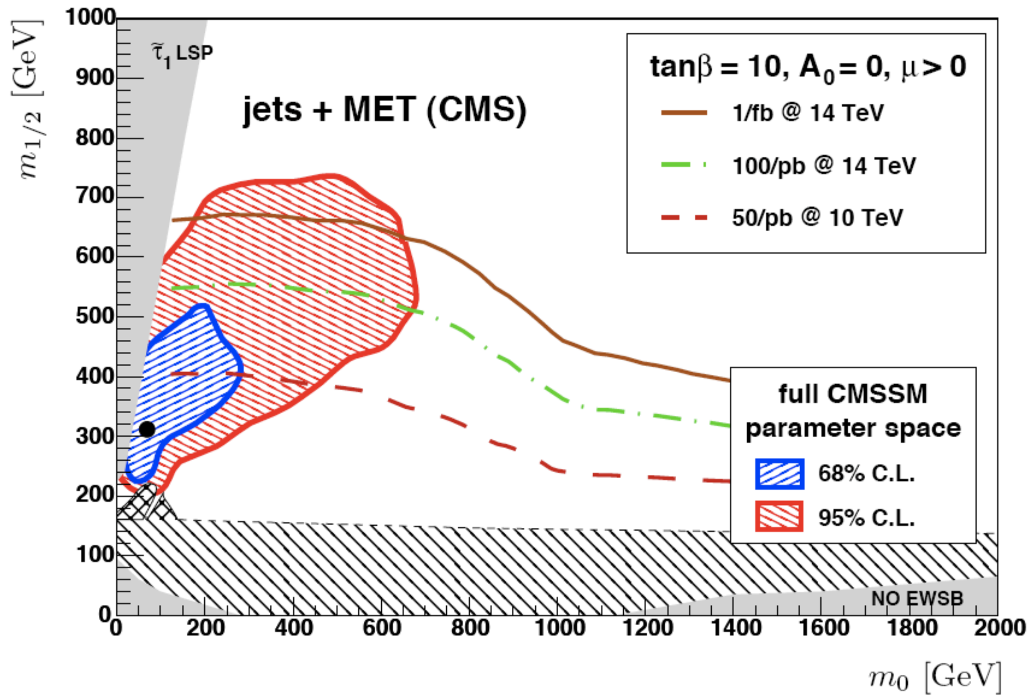
O. Buchmüller et al,
0808.4128, 0907.5568
(“Mastercode”)

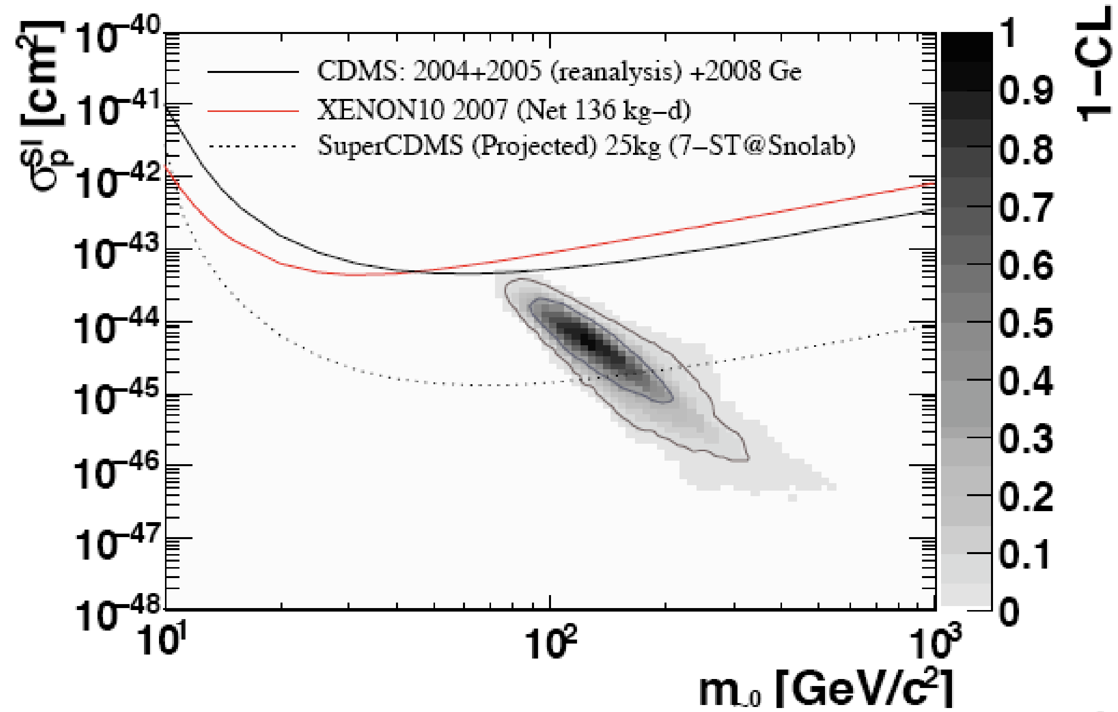
Fits: Frequentist

LHC potential

Direct DM search

CMSSM





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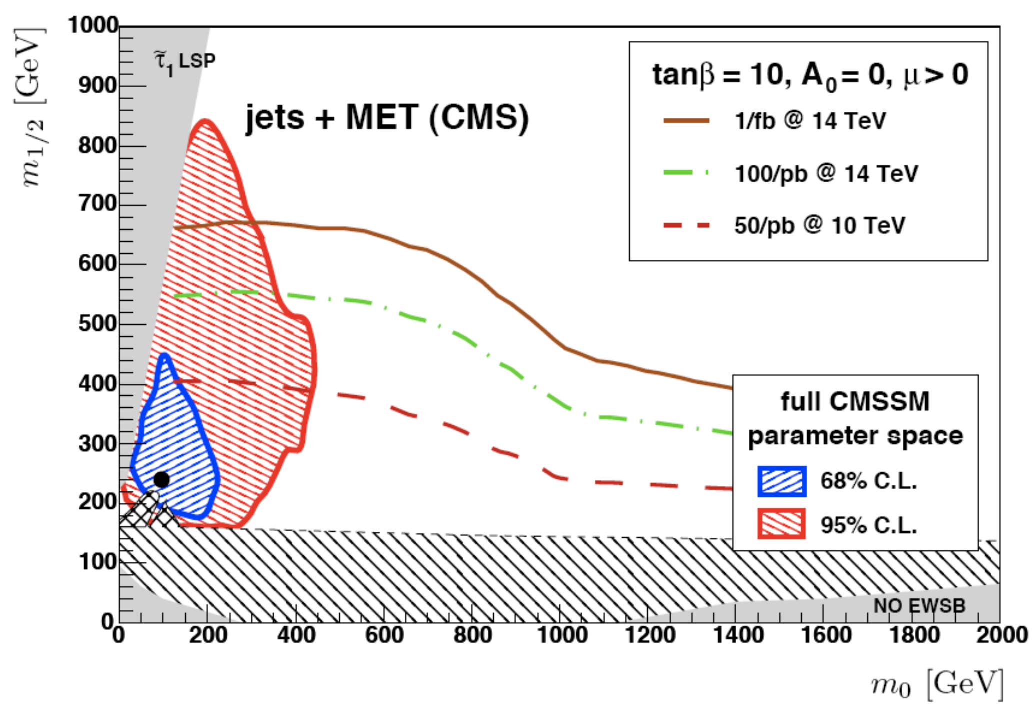

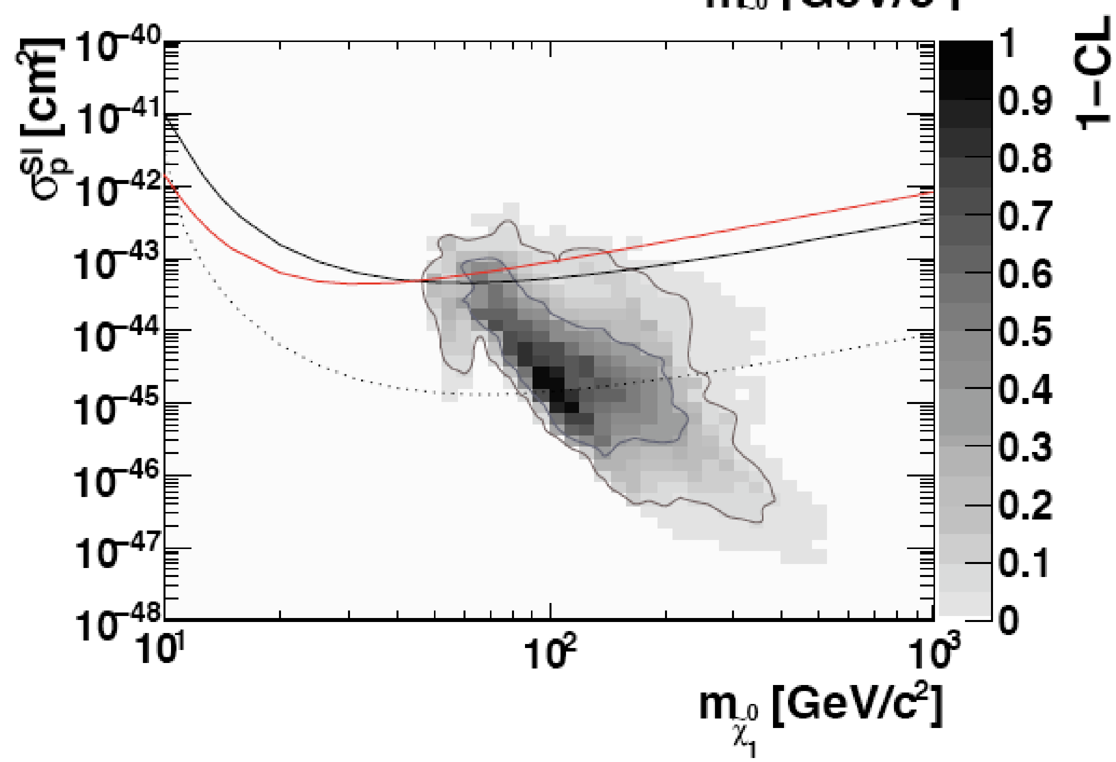

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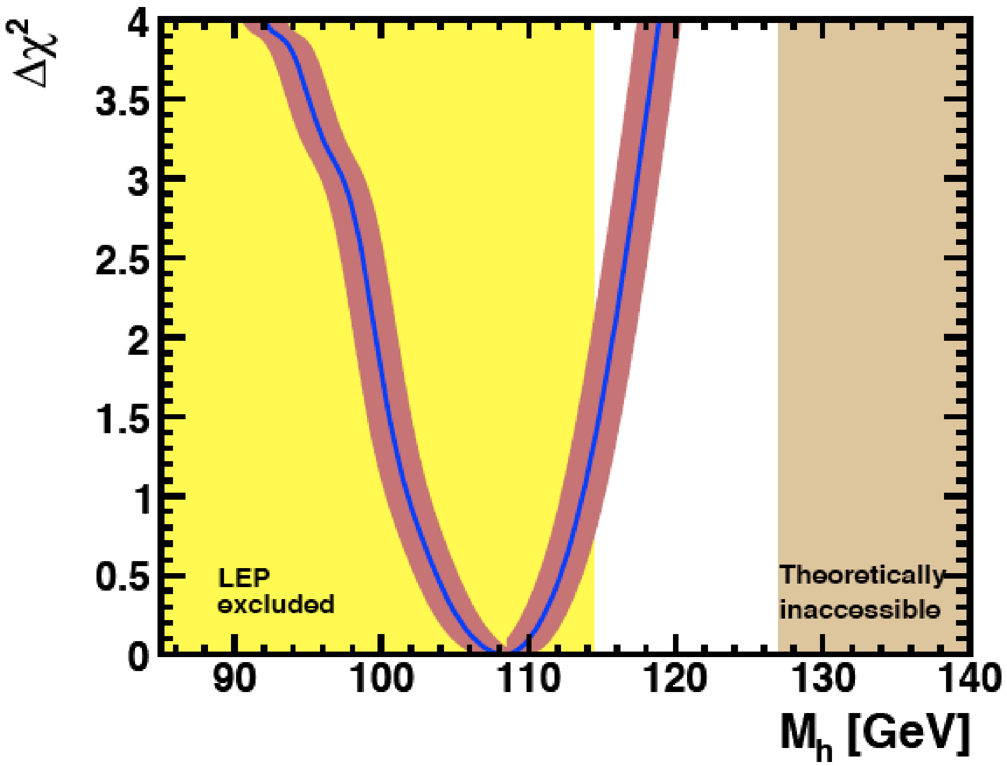
Fit of Higgs mass

CMSSM



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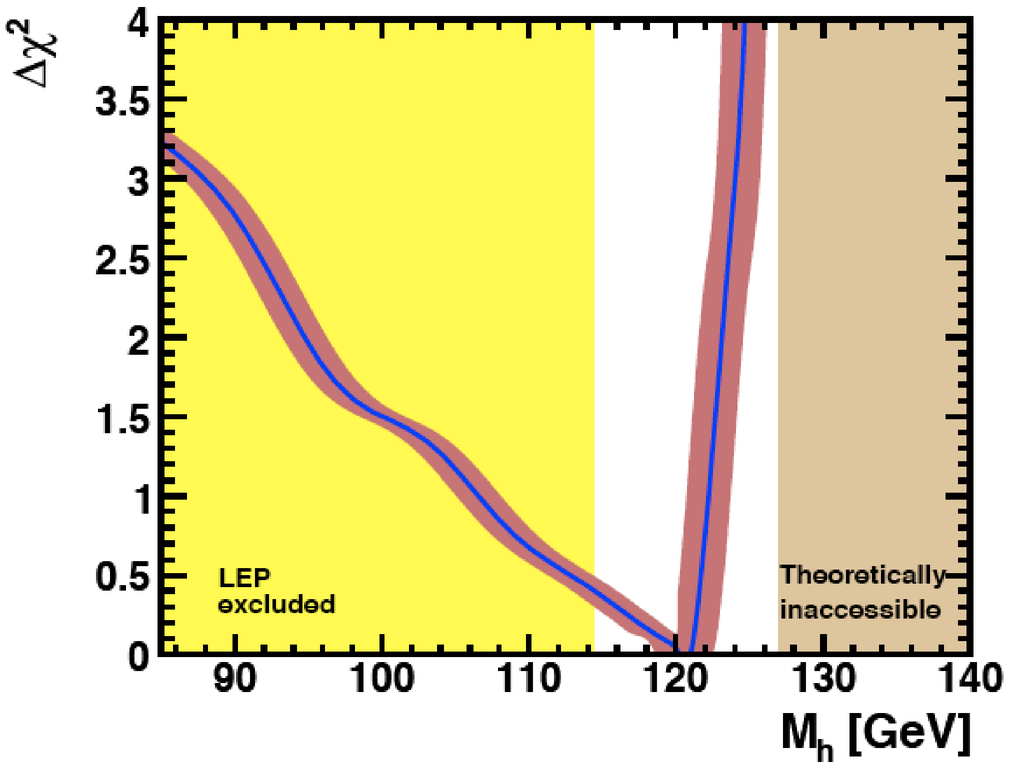

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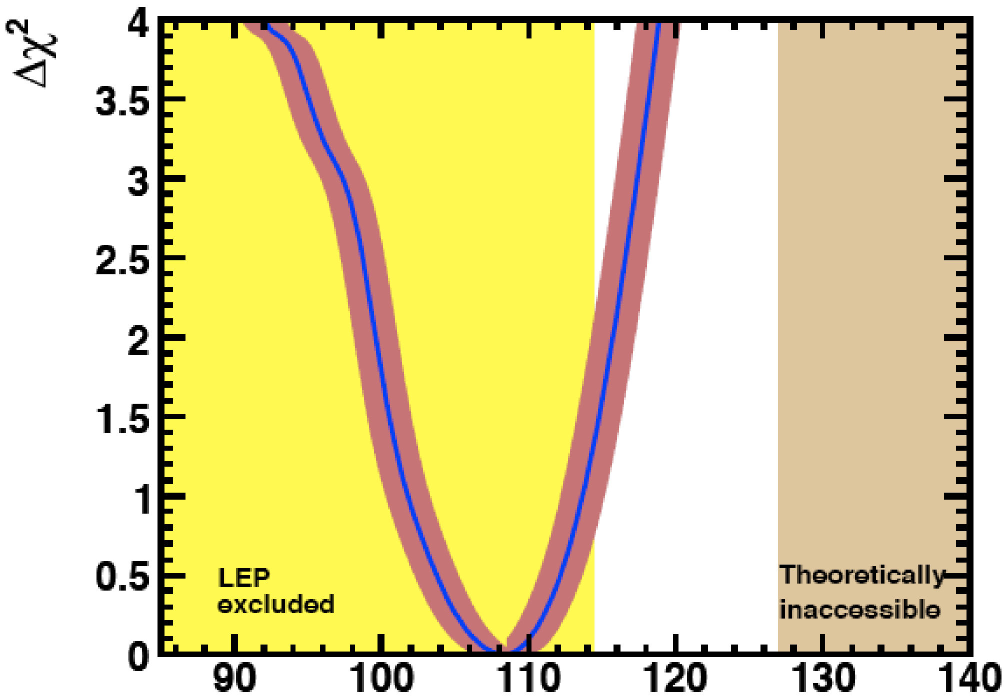

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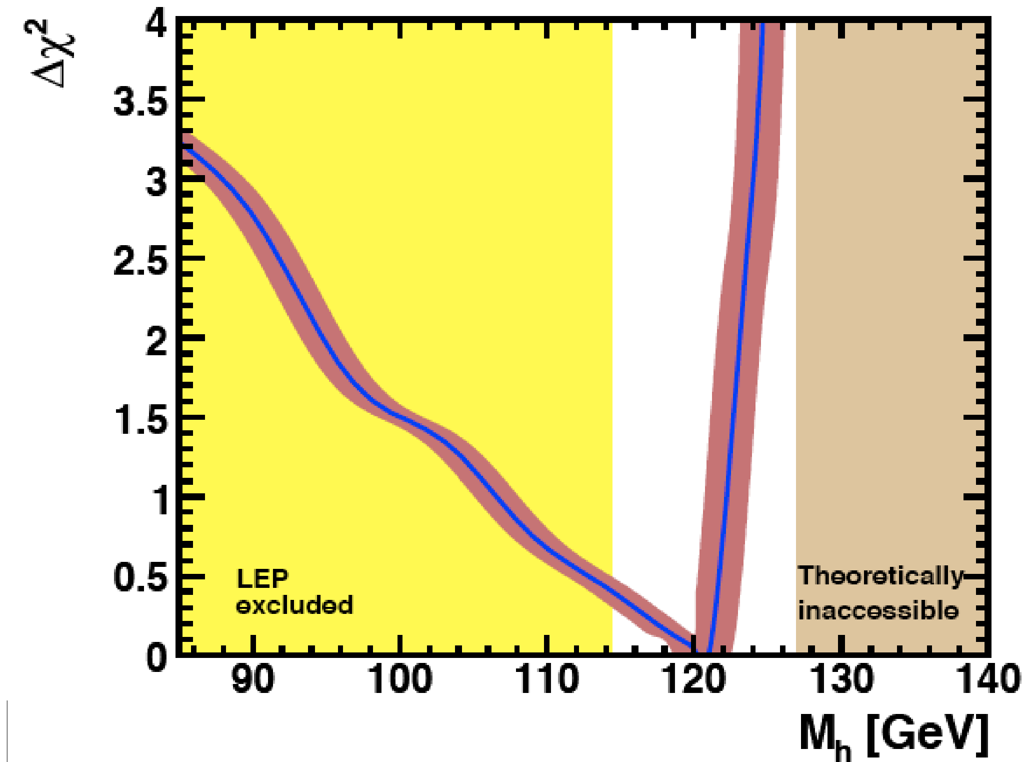
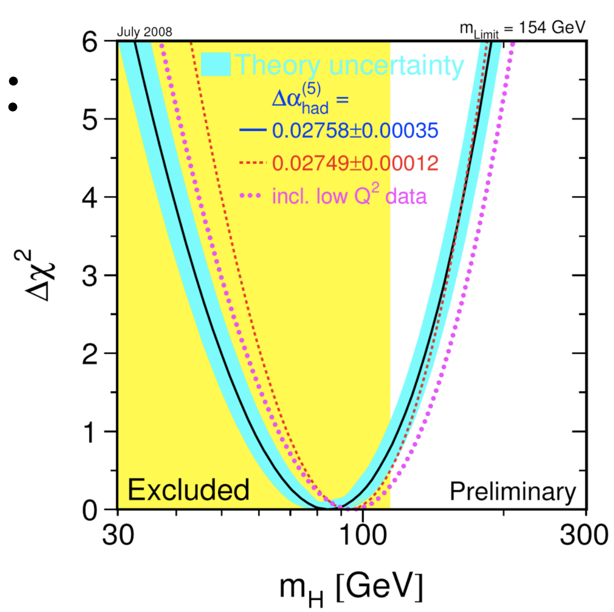


SM:



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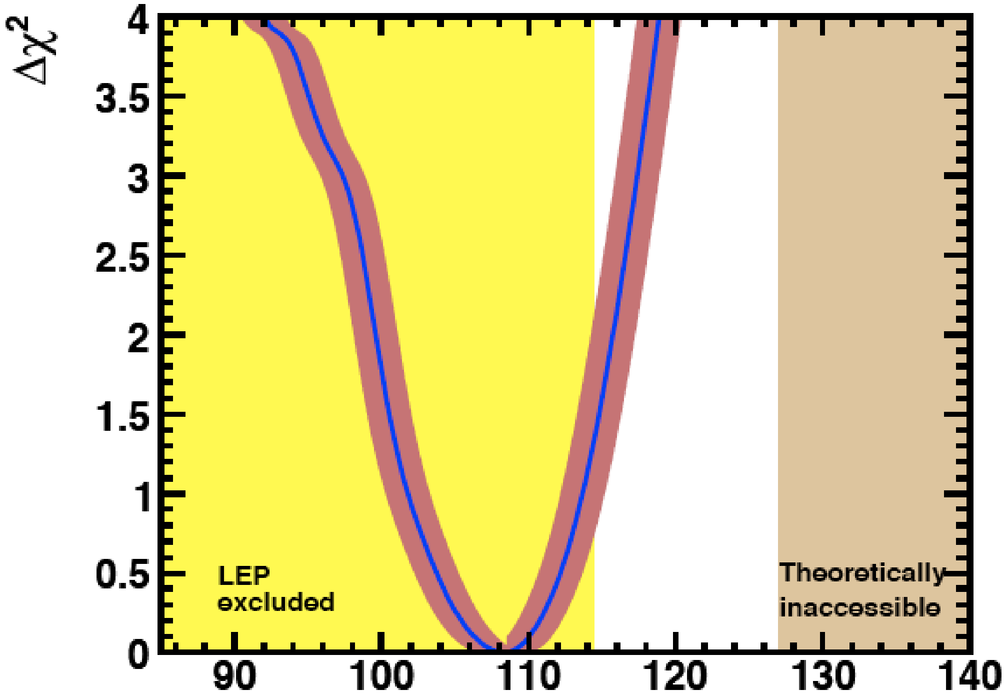

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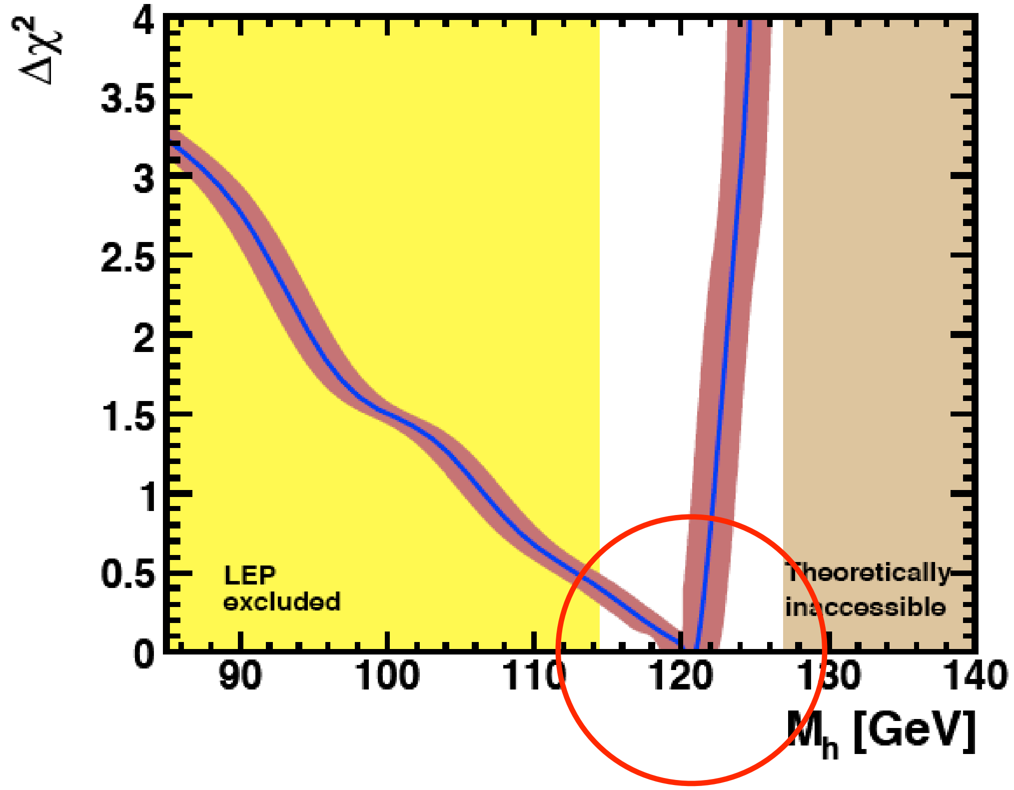

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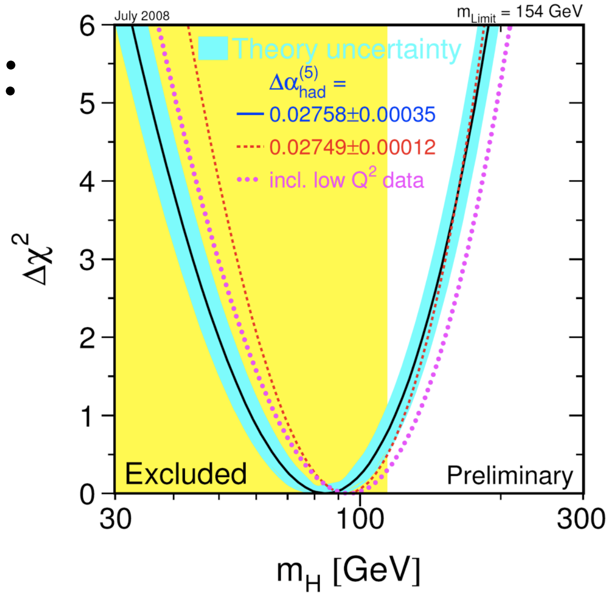


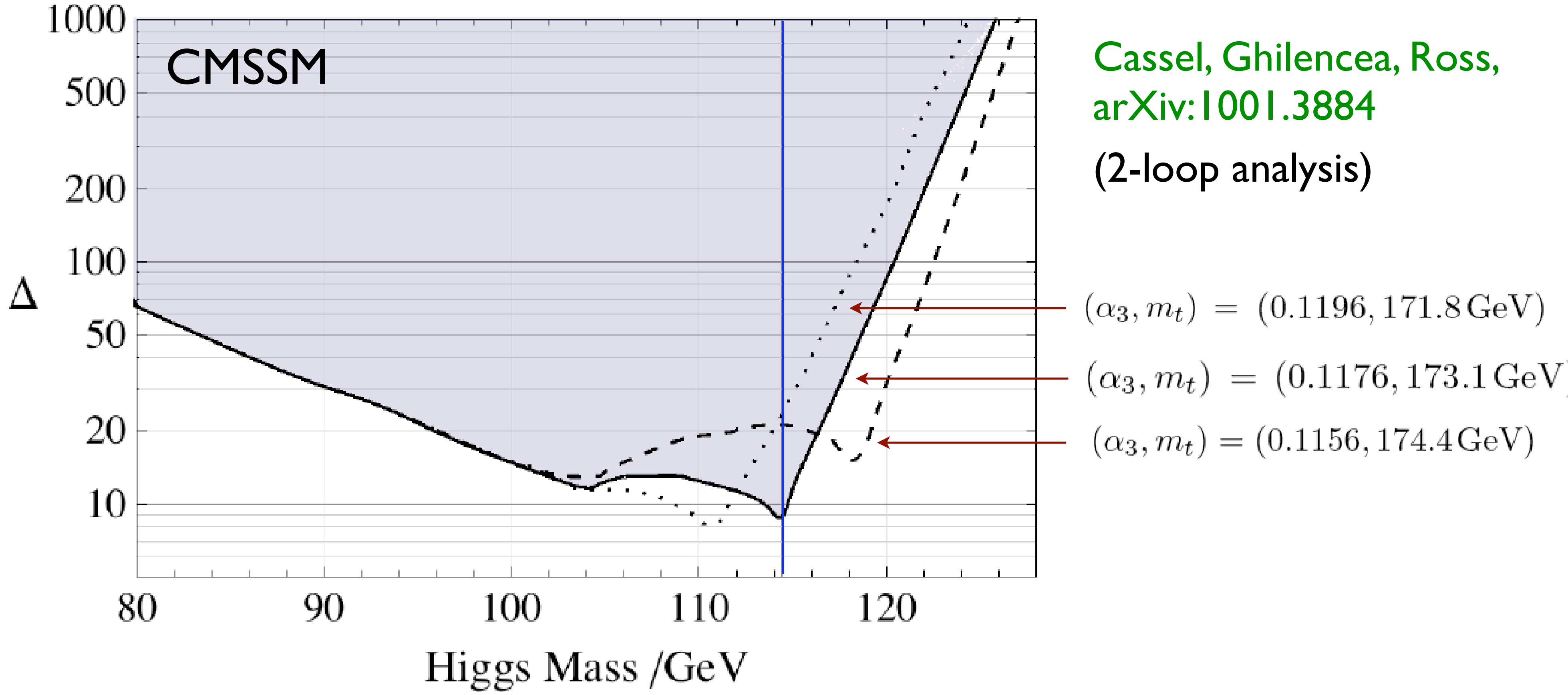
above the LEP bound!

see also
Barbieri et al.,
Chankowski et al.,
....

The finetuning price

- Finetuning = sensitivity of EW scale to input parameters

$$\frac{M_Z^2}{2} \approx -m_{H_2}^2 - |\mu|^2$$



Cassel, Ghilencea, Ross,
arXiv:1001.3884

(2-loop analysis)

$$\Delta \equiv \max \left|\Delta_p\right|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}$$

Cassel, Ghilencea, Ross,
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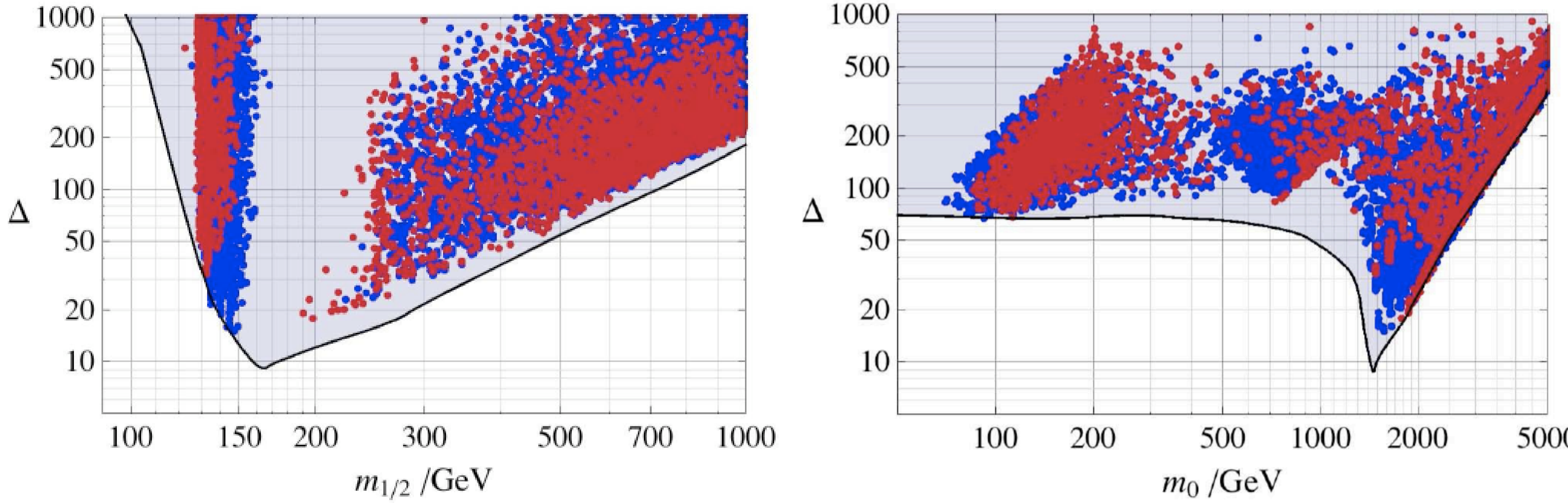
CMSSM low finetuning



red points:
Relic density
within WMAP
limit (at 3σ)

NB: points with lowest finetuning lie in the focus point region

- gaugino-higgsino mixing
- light gluino
- Xsections a few pb at 7TeV LHC

$BR(\tilde{g} \to \tilde{\chi}_i^0 g) \sim 10-20\%$

$BR(\tilde{g} \to \tilde{\chi}_i^0 b\bar{b}, \tilde{\chi}_i^{\pm} tb) \sim 20\%$

h^0	114.5	$\tilde{\chi}_1^0$	79	$\tilde{b}_1$	1147	$\tilde{u}_L$	1444
H^0	1264	$\tilde{\chi}_2^0$	142	$\tilde{b}_2$	1369	$\tilde{u}_R$	1446
$H^{\pm}$	1267	$\tilde{\chi}_3^0$	255	$\tilde{\tau}_1$	1328	$\tilde{d}_L$	1448
A^0	1264	$\tilde{\chi}_4^0$	280	$\tilde{\tau}_2$	1368	$\tilde{d}_R$	1446
$\tilde{g}$	549	$\tilde{\chi}_1^{\pm}$	142	$\tilde{\mu}_L$	1406	$\tilde{s}_L$	1448
$\tilde{\nu}_{\tau}$	1366	$\tilde{\chi}_2^{\pm}$	280	$\tilde{\mu}_R$	1406	$\tilde{s}_R$	1446
$\tilde{\nu}_{\mu}$	1404	$\tilde{t}_1$	873	$\tilde{e}_L$	1406	$\tilde{c}_L$	1444
$\tilde{\nu}_e$	1404	$\tilde{t}_2$	1158	$\tilde{e}_R$	1406	$\tilde{c}_R$	1446

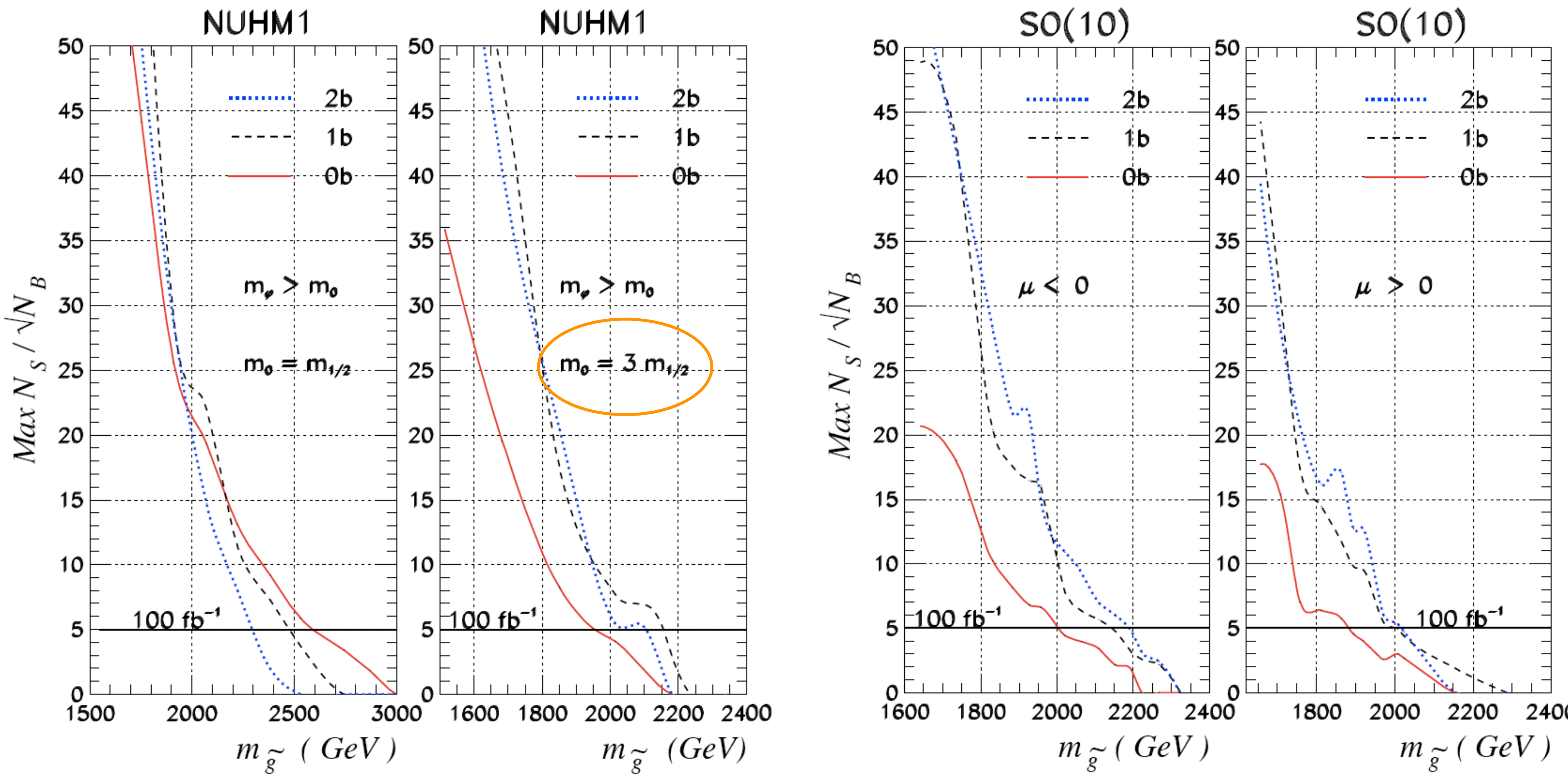
upper limits for Δ<100

$\tilde{g}$	χ_1^0	χ_2^0	χ_3^0	χ_4^0	$\chi_1^{\pm}$	$\chi_2^{\pm}$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
1720	305	550	660	665	550	670	2080	2660	2660	3140

Kadala, Mercadante, Mizukoshi, Tata,
arXiv:0803.0001

Importance of b-tagging

- Requiring 1, 2 or more b-jets can significantly enhance the signal/bg ratio in certain scenarios, e.g., 15-20% in the CMSSM focus point region.

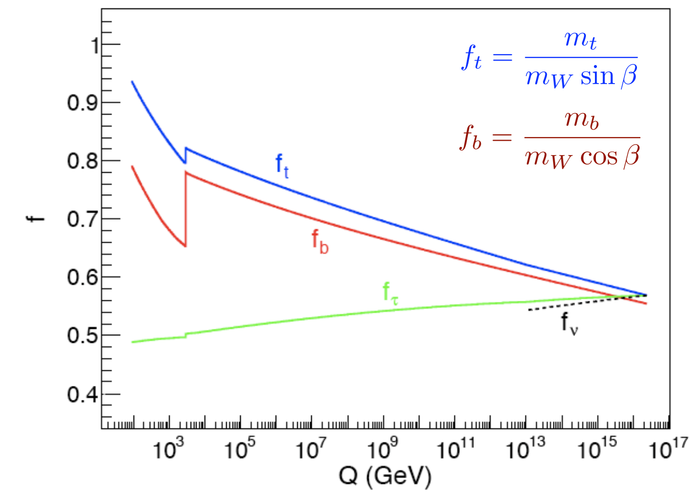


14 TeV

- Typical if 3rd generation is lighter then 1st/2nd generation and $m_{\tilde{g}} \ll m_{\tilde{q}}$; enhances gluino decays into t or b via on- or off-shell stop/sbottom

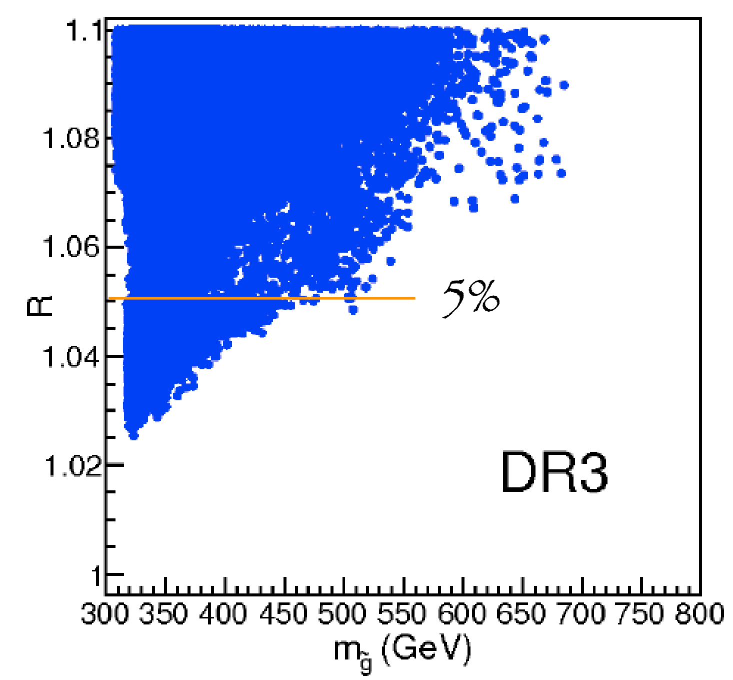
SO(10): Yukawa-unified SUSY

- SUSY GUTs based on SO(10) are particularly compelling
  - unify all matter of one generation in a 16-dim spinor (incl. r.h. neutrino!)
  - automatic anomaly cancellation



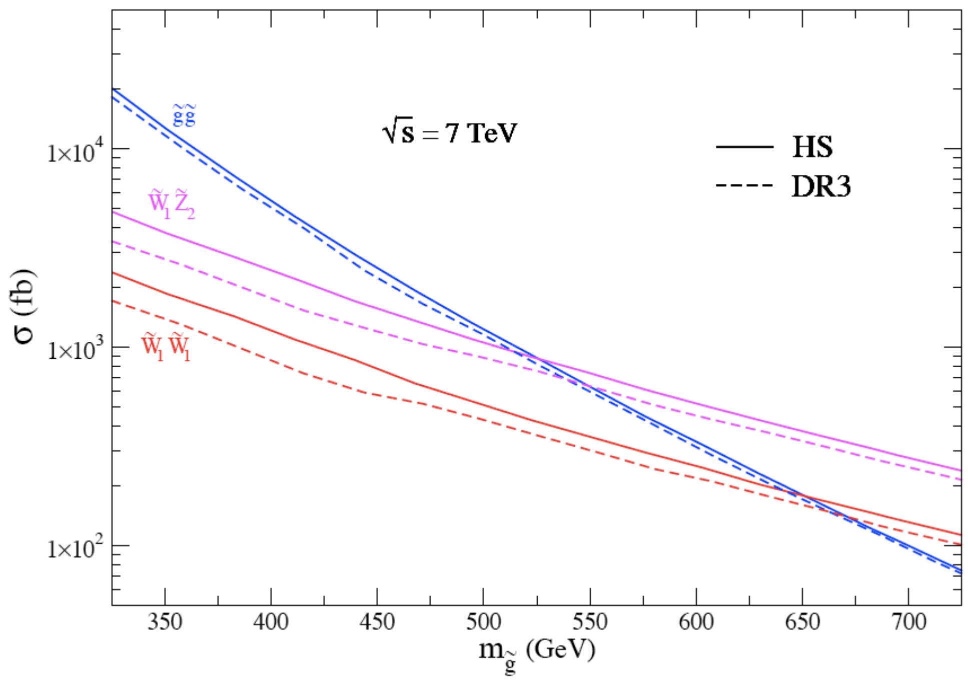
- The simplest realizations (Higgs in a 10-plet) require t-b-tau Yukawa coupling unification in addition to gauge coupling unification at M_{GUT}.

- Typical mass spectrum:
  - 1st/2nd generation scalars in the 5-15 TeV range,
  - 3rd gen. scalars, Higgses and higgsinos ca. 1-3 TeV,
  - gauginos: LSP ~ 50-80 GeV, gluino ~ 300-500 GeV!
  - c.f "effective SUSY" by Cohen, Kaplan, Nelson '1996



See Baer et al, 0801.1831, 0809.0710, 0812.2693, 0908.0134, 0910.2988, 0911.4739.

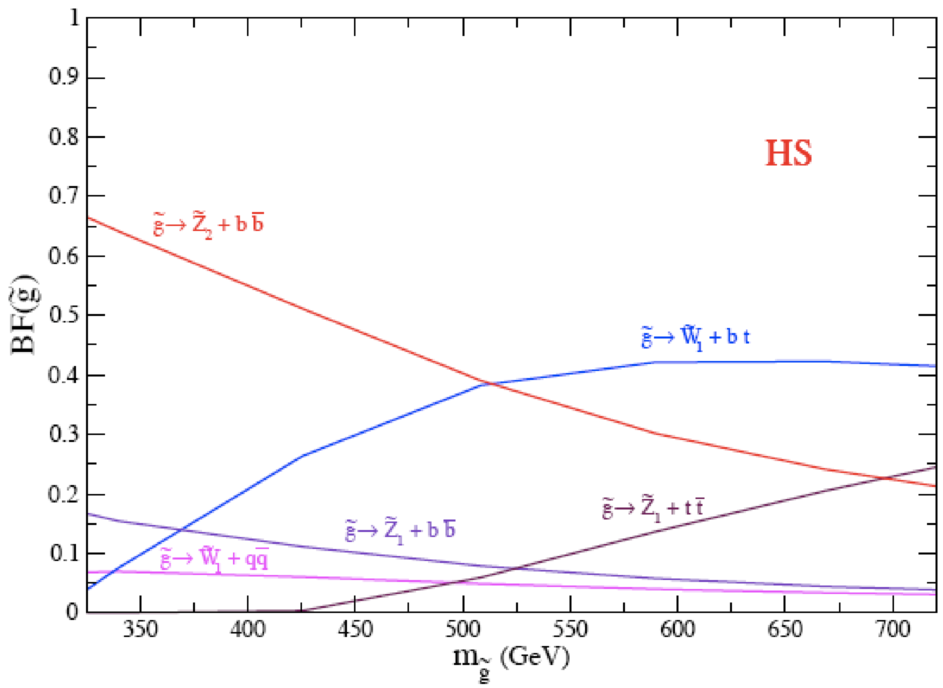
LHC reach at 7 TeV

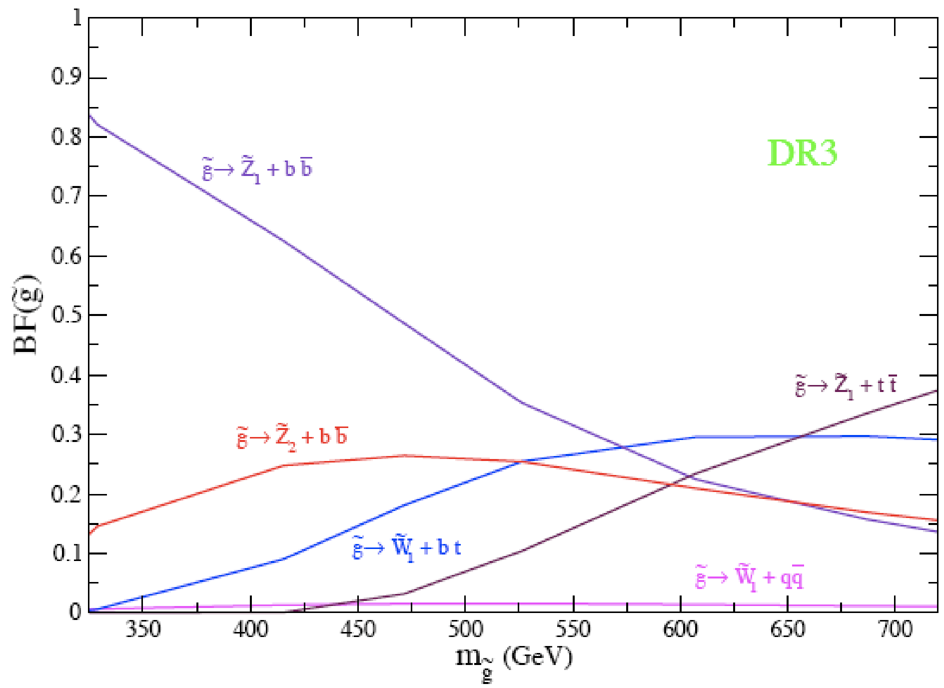


Gluino-pair prod. dominated by gg fusion.
σ(LO)~1 pb at m(gluino)~525 GeV

We consider model lines for HS and DR3 *) cases as funct. of m(gluino) up to 700 GeV.

Gluino decays are dominanted by heavy flavours: $\tilde{g} \to \tilde{\chi}^0_{1,2} b\bar{b}$, $\tilde{\chi}^{\pm}_1 tb$



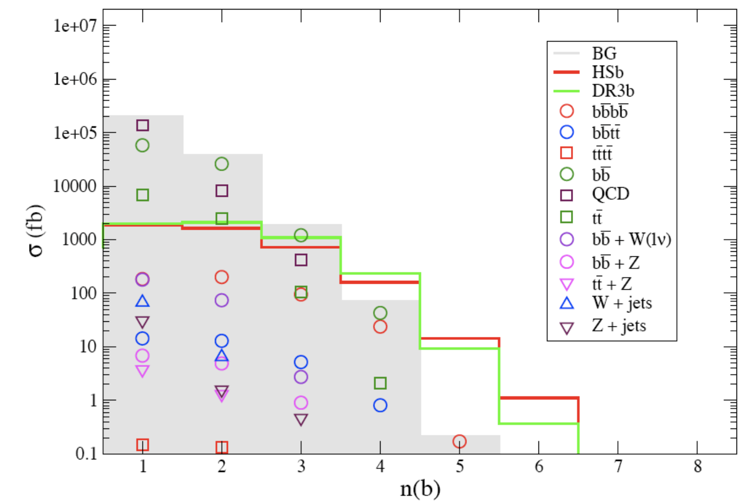


*) HS: only Higgs masses split, DR3: full D-term splitting, see 0908.0134

LHC reach at 7 TeV

(theorists' simulation)

Event simulation:

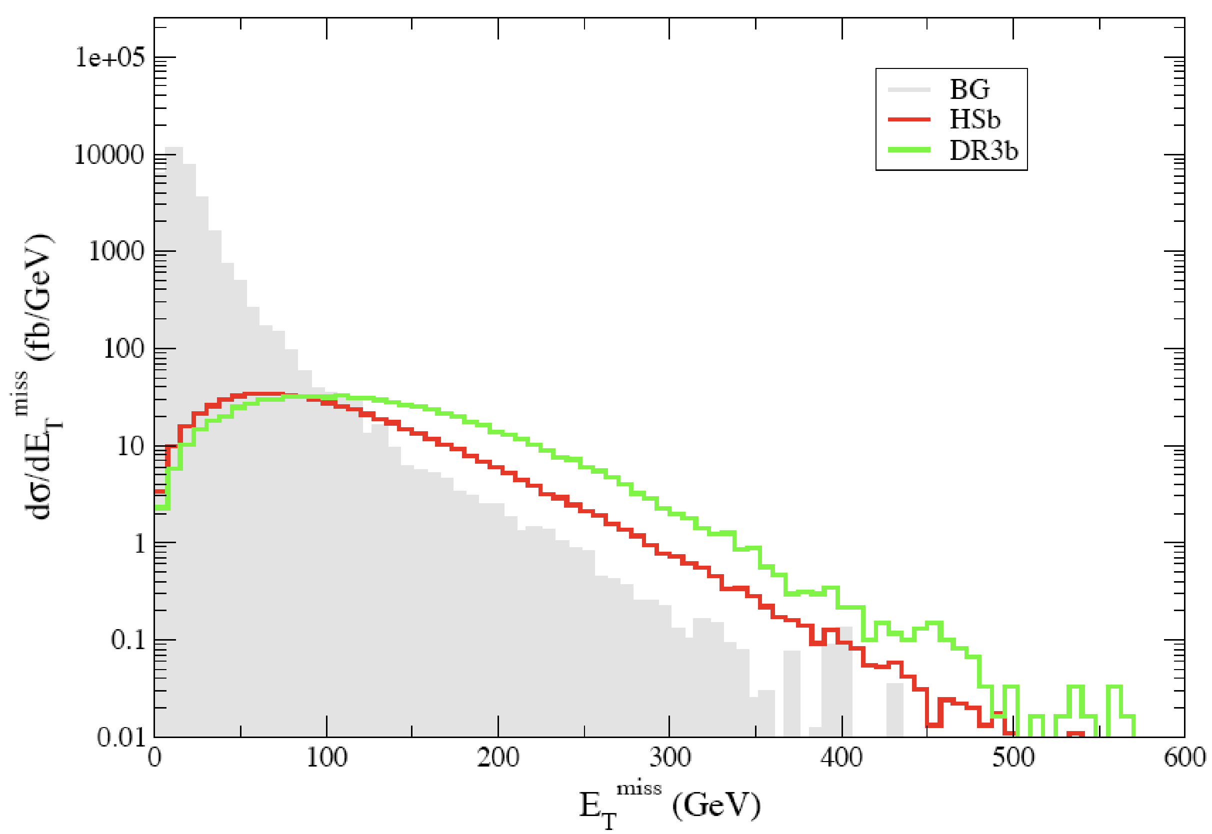


- Isajet 7.79 for the signal
- QCD, 2- and 3-bdy BGs with Alpgen
- 4t, 4b, 2t2b BGs with Madgraph
- Phythia for showering and hadronization
- Generic LHC detector simulation

Basic Cuts "C0":

- n(jets)≥4 with p_T > 50GeV
- hardest jet p_T >100 GeV
- $S_T \geq 0.2$ (transv sphericity)
- n(b) ≥ 1 (b-eff. 60%)

Results after C0-based selection			
	$\sigma(n(b) \geq 3)$	$\sigma(n(b) \geq 4)$	$\sigma(\mathrm{OS})$
HSb	899 fb	176 fb	99 fb
DR3b	1334 fb	243 fb	22 fb
BG	1911 fb	70 fb	11 fb



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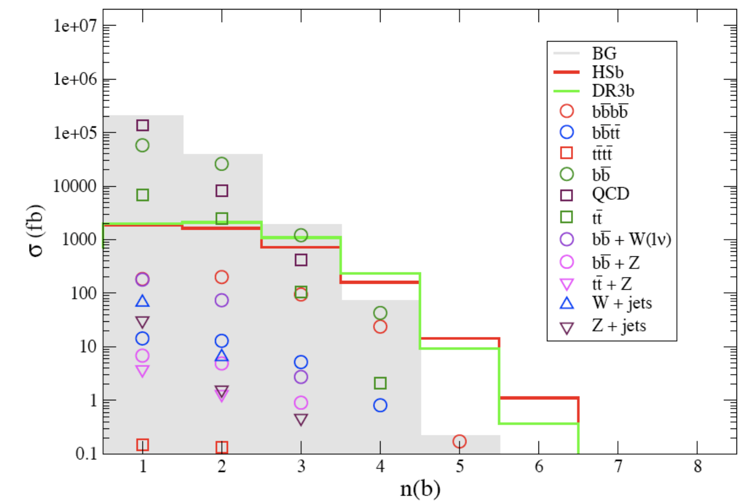
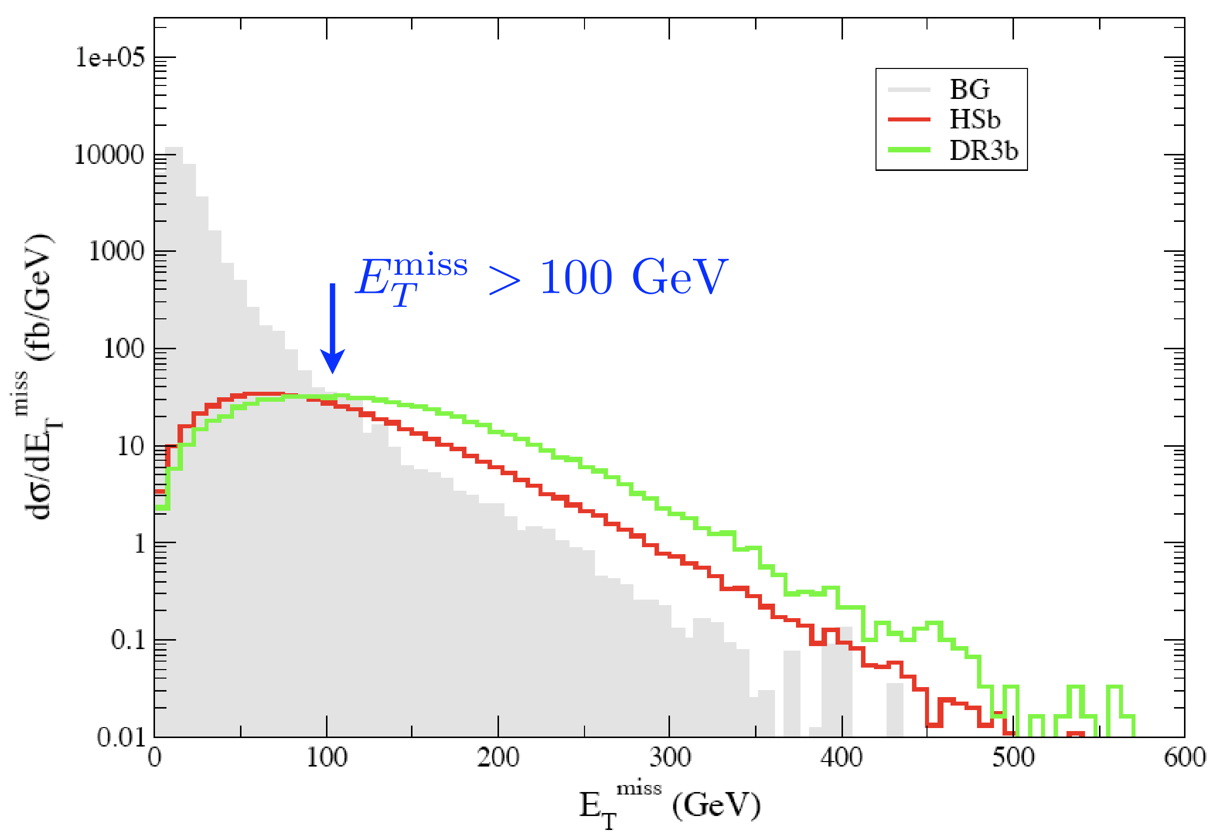
- QCD, 2- and 3-bdy BGs with Alpgen
- 4t, 4b, 2t2b BGs with Madgraph
- Phythia for showering and hadronization
- Generic LHC detector simulation



Basic Cuts "C0":

- n(jets)≥4 with $p_T > 50$GeV
- hardest jet $p_T > 100$ GeV
- $S_T \geq 0.2$ (transv sphericity)
- $n(b) \geq 1$ (b-eff. 60%)

Results after C0-based selection			
	$\sigma(n(b) \geq 3)$	$\sigma(n(b) \geq 4)$	$\sigma(\mathrm{OS})$
HSb	899 fb	176 fb	99 fb
DR3b	1334 fb	243 fb	22 fb
BG	1911 fb	70 fb	11 fb



LHC reach at 7 TeV

(theorists' simulation)

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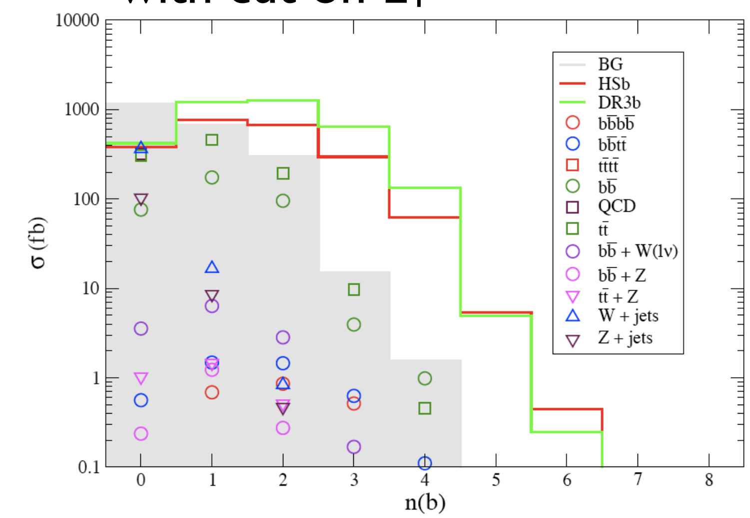
with cut on E_T^{miss}



Basic Cuts "C0":

- n(jets)≥4 with p_T > 50GeV
- hardest jet p_T >100 GeV
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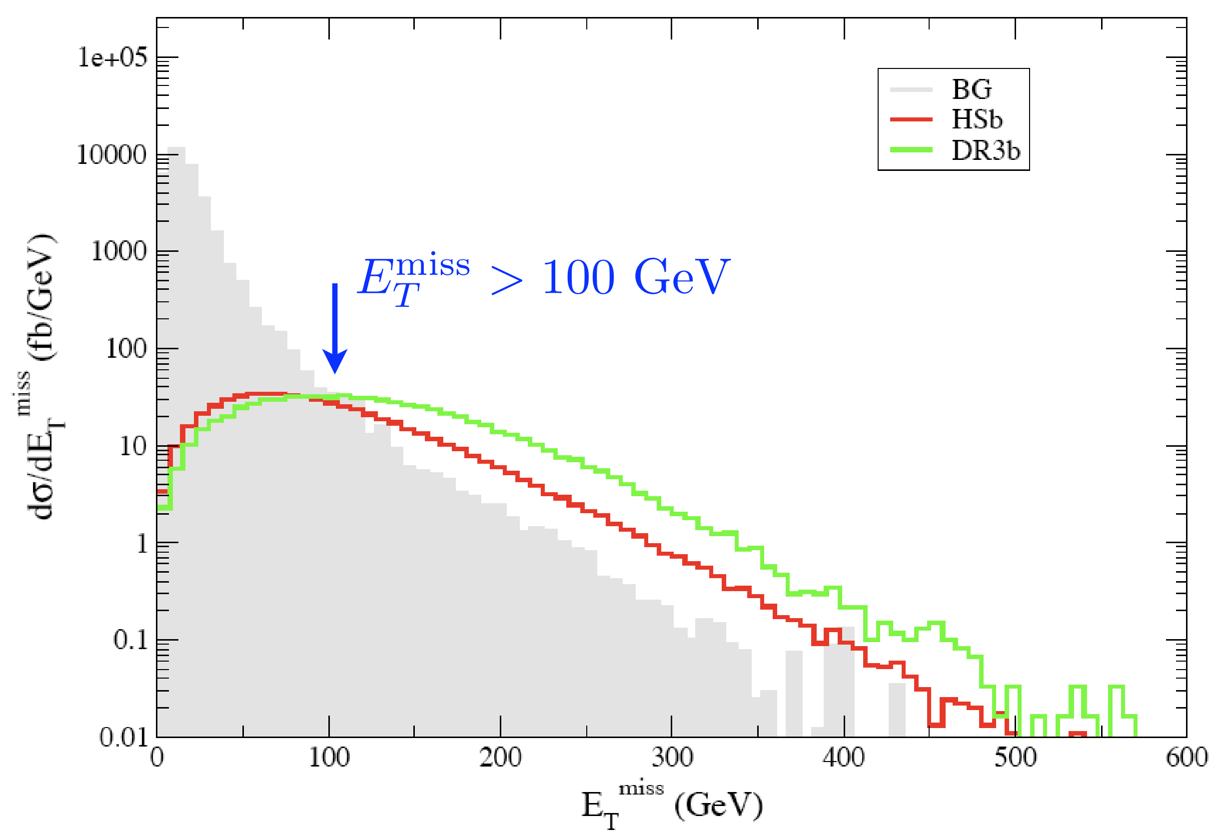
Results after C1-based selection			
	$\sigma(n(b) \geq 3)$	$\sigma(n(b) \geq 4)$	$\sigma(OS)$
HSb	364 fb	68 fb	81 fb
DR3b	782 fb	139 fb	23 fb
BG	16 fb	2 fb	9 fb



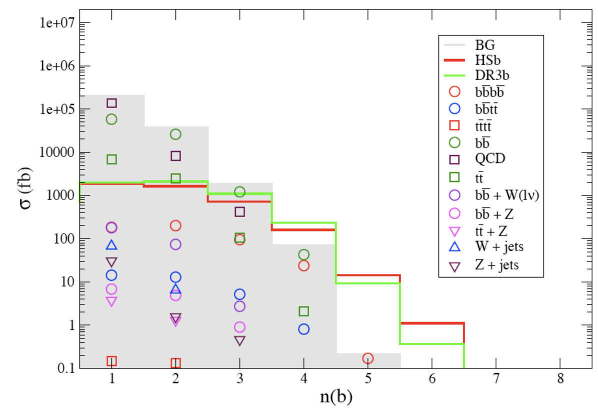
Baer et al, arXiv:0911.4739

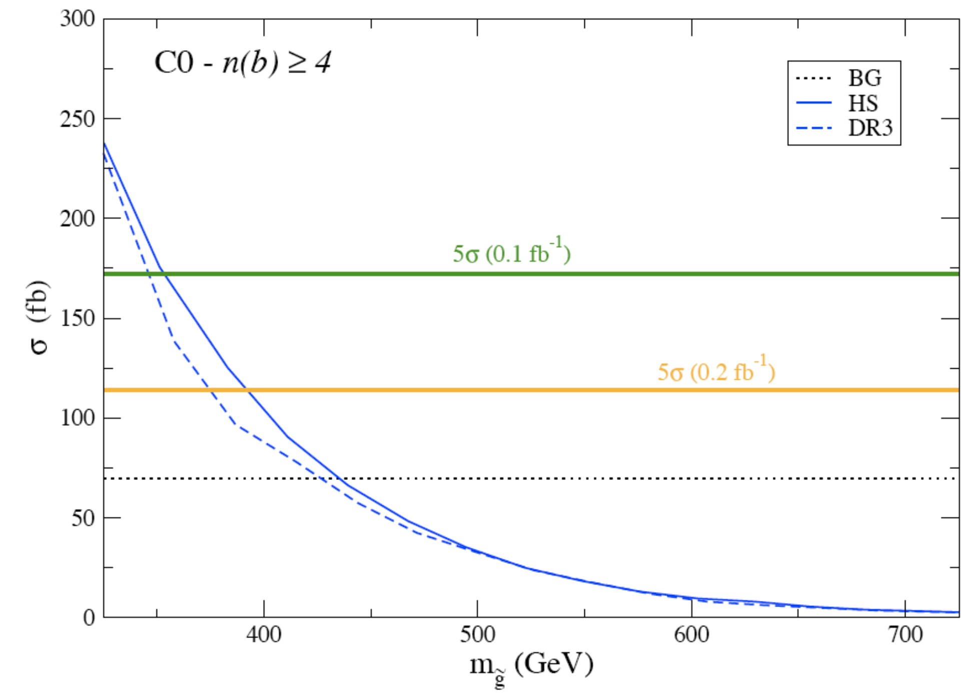
LHC reach at 7 TeV

(theorists' simulation)

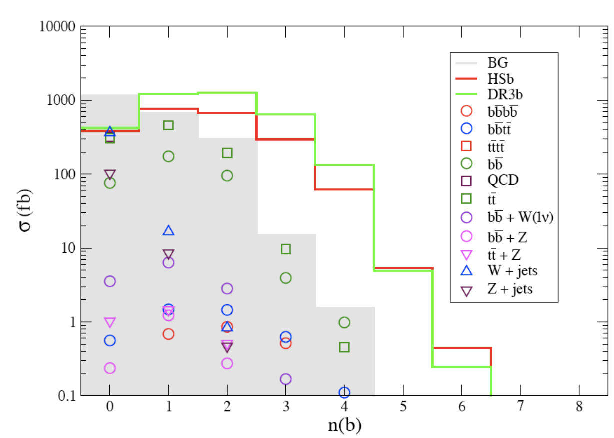
Without missing energy measurement:
up to m(gluino)=400 GeV with 0.2 fb^{-1} of data
requiring 4 b-jets

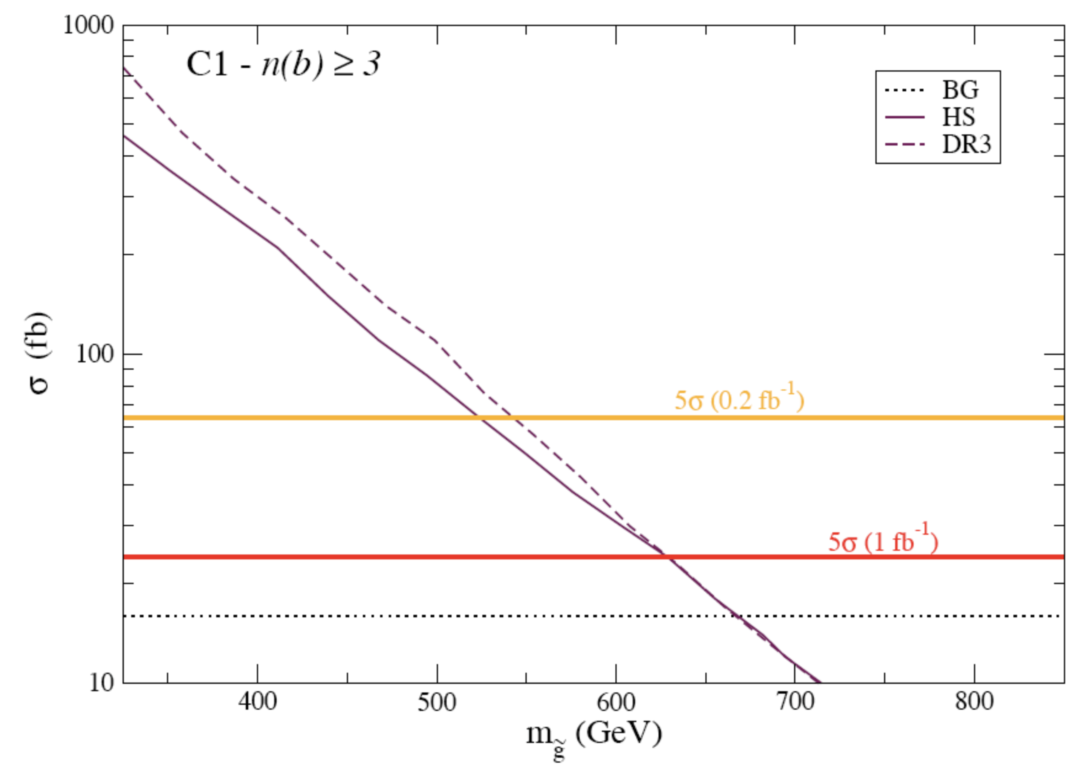
$\lesssim$ Tevatron with 10 fb^{-1}





With reliable MET measurement:
reach up to m(gluino)=540-630 GeV
with 0.2-1 fb^{-1} of data,
n(b) ≥ 3





Conclusions

- MSSM and constrained versions thereof are in a good shape
  - large regions of parameter space compatible with exp. constraints
  - tension with LEP Higgs limit can be evaded
  - finetunig price may not be too high (CMSSM preferred)
- Important development of fitting tools
  (Sfitter, Fittino, SuperBayes, Mastercode, many private codes)
- Much of recent work has gone into Bayesian inference;
  fits show strong prior dependence → need more data
- Tevatron/LHC have good potential for "effective SUSY"
  (light gauginos [gluino], TeV-scale 3rd generation, multi-TeV 1st/2nd gen)
- Example: Yukawa-unified SUSY SO(10)
- b-tagging may be essential for early SUSY discovery

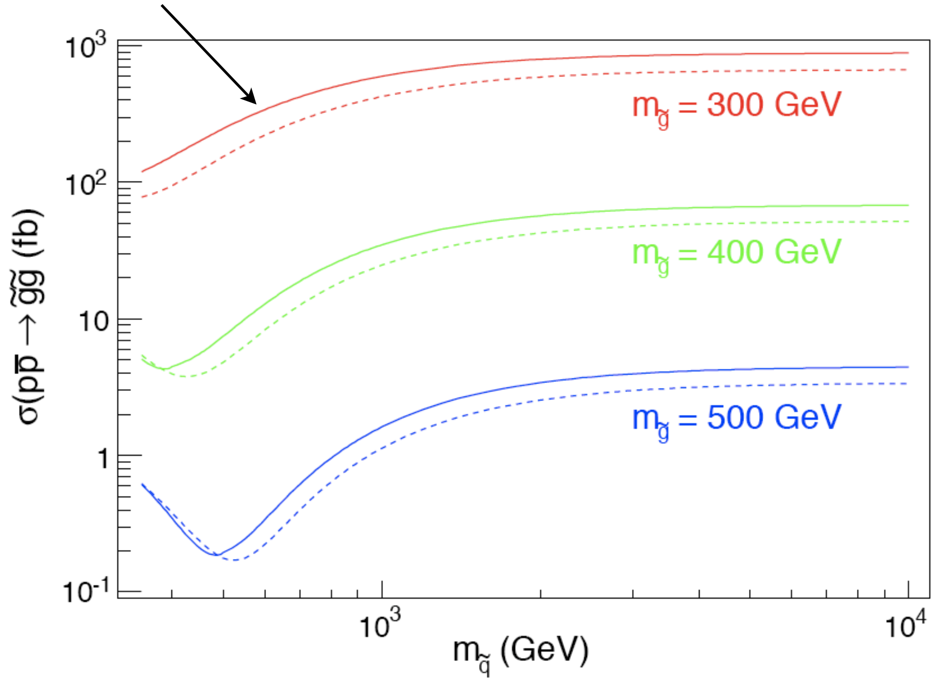
Exciting times !

Backup

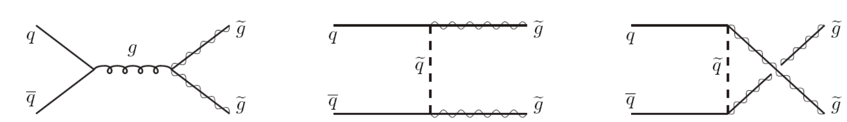
Baer et al, arXiv:0910.2988

Tevatron reach

current mSUGRA limit
for heavy squarks ($2fb^{-2}$)



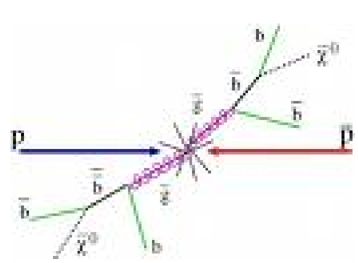
Gluino-pair prod. dominated by $q\bar{q}$ fusion. Negative interference of s-, t-, u-channels for m(squark)~m(gluino)!

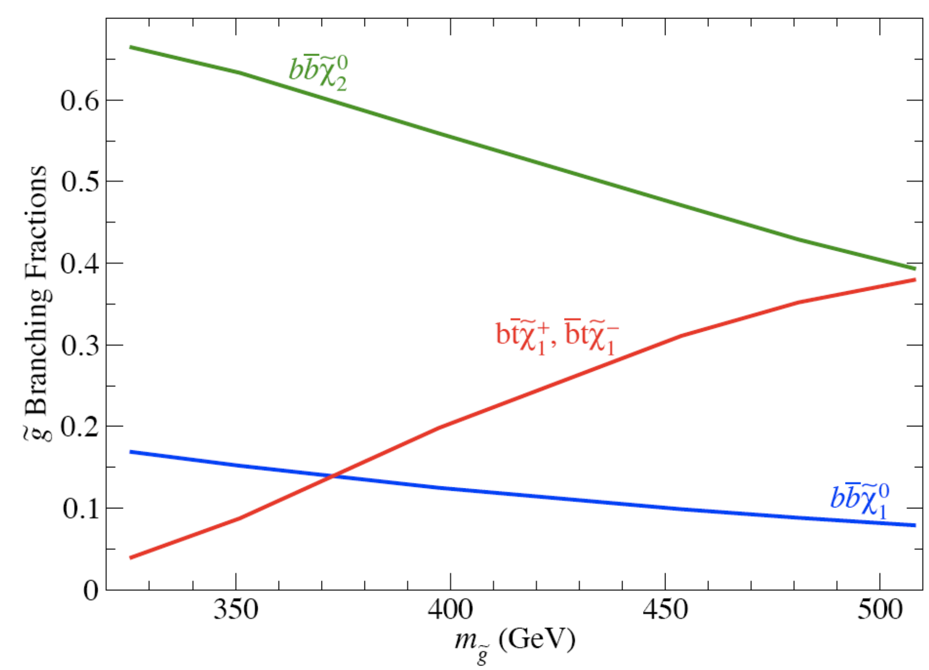


Xsection grows with increasing squark mass!

Gluino decays dominated by $\tilde{\chi}_2^0 b\bar{b}$ channel. We adopt a YU model line by starting from a HS point with m_{16}=10 TeV and R~1.02 and varying $m_{1/2}$.

$$m_{1/2} = 35 - 100 \text{ GeV},$$
$$m_{\tilde{g}} = 325 - 508 \text{ GeV},$$
$$R \to 1.07$$





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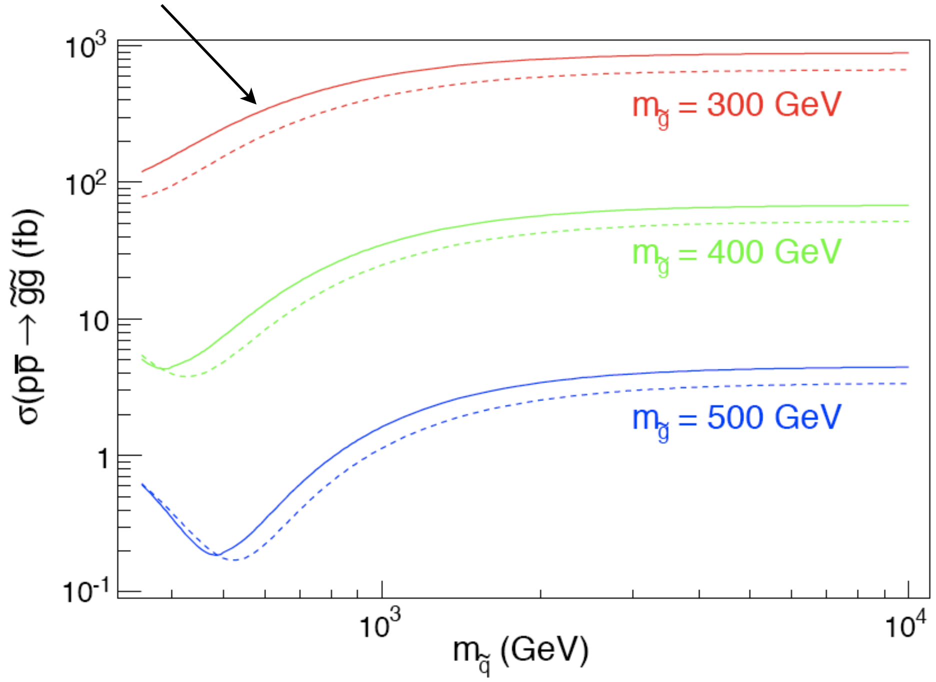

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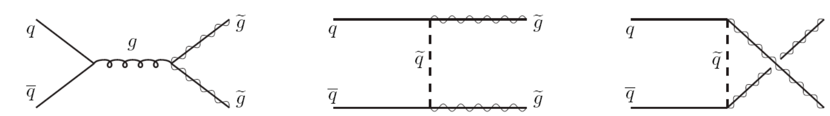

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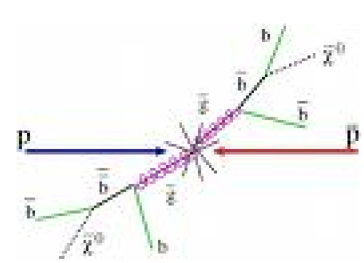

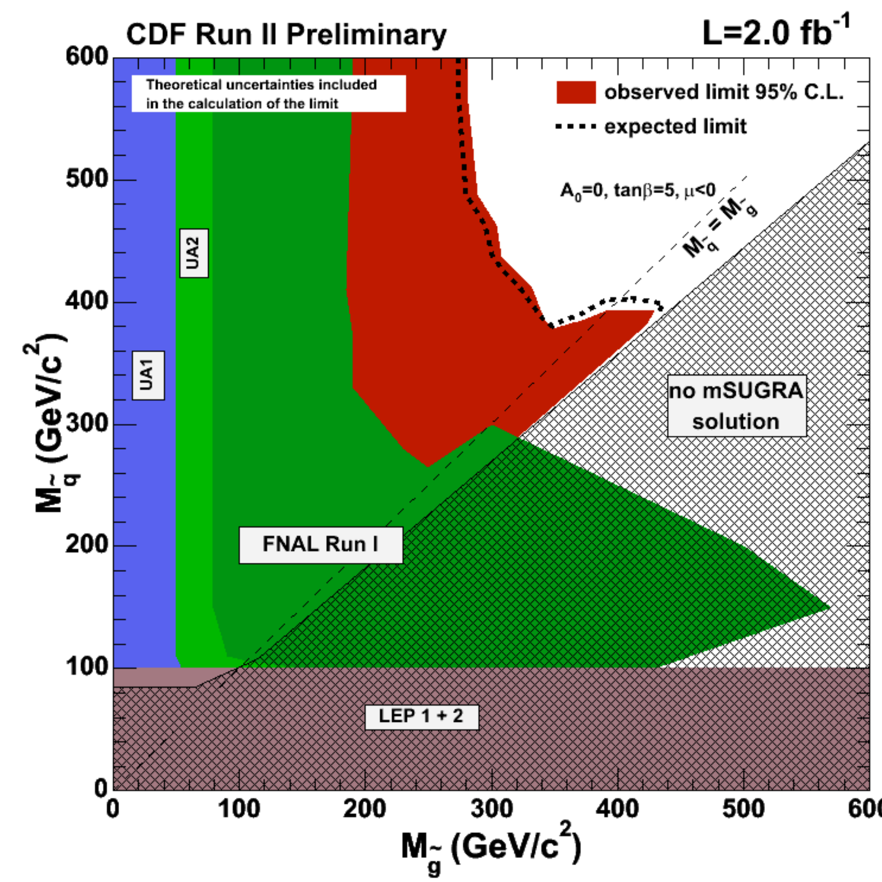

Baer et al, arXiv:0910.2988

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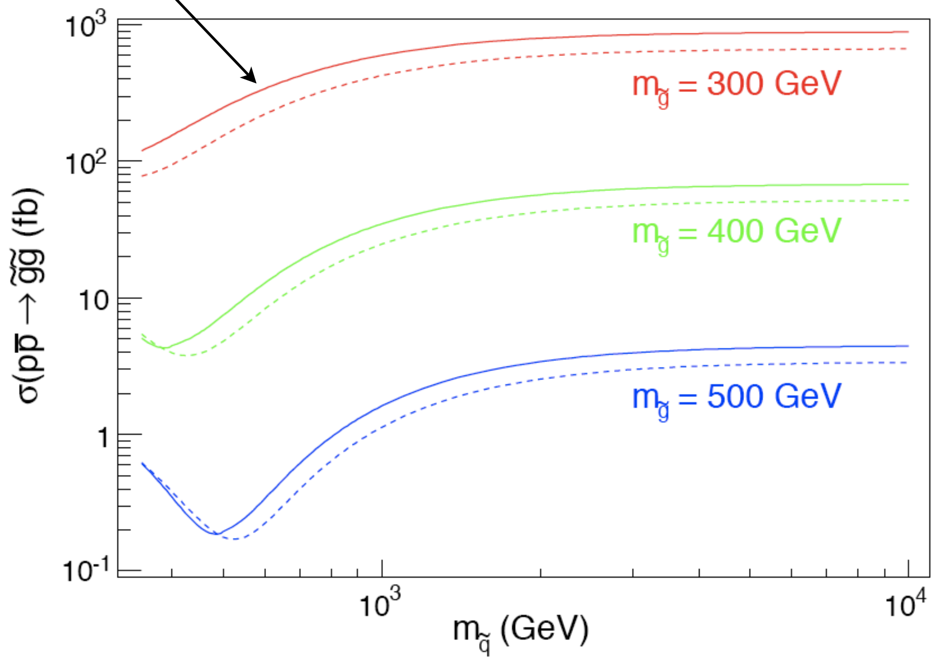

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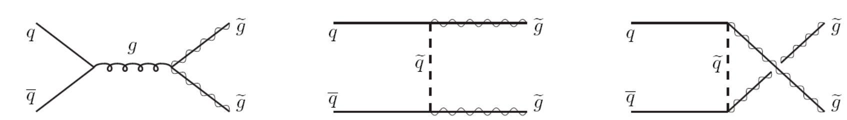

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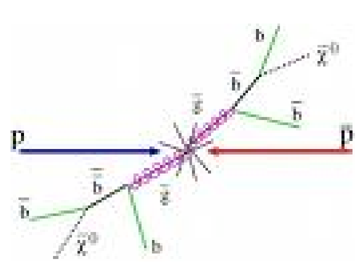

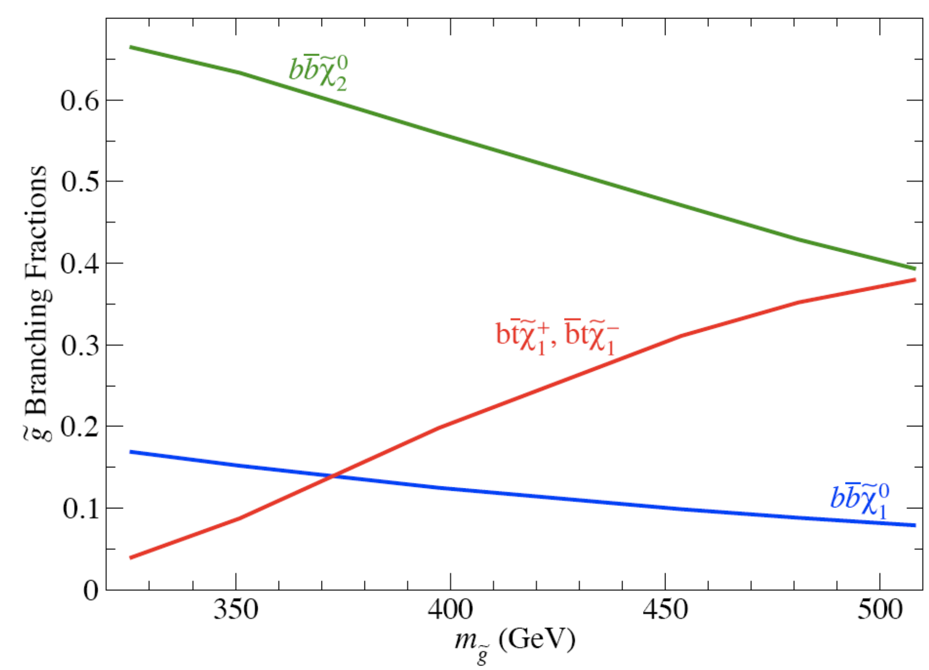

Baer et al, arXiv:0910.2988

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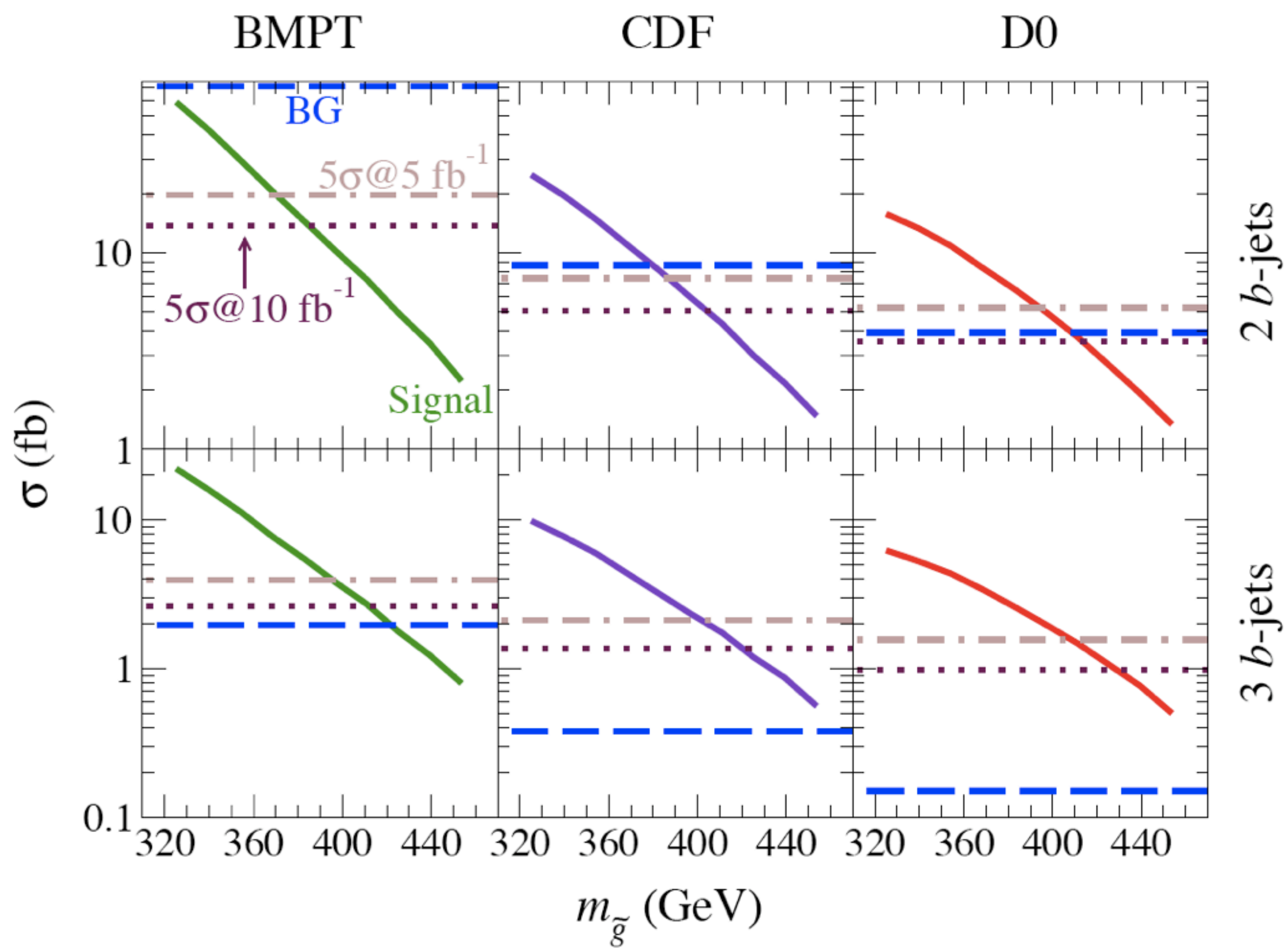
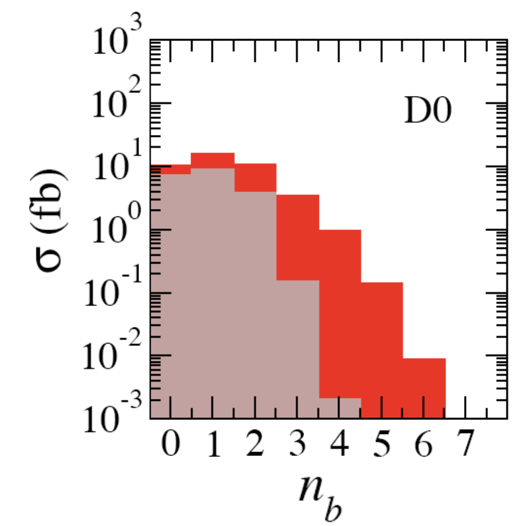
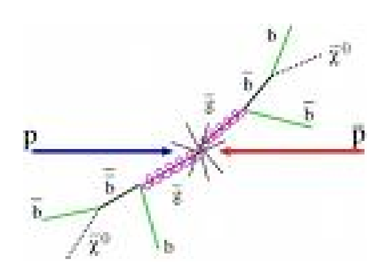




cuts	$E_T^{\rm miss}$	H_T	$E_T(j1)$	$E_T(j2)$	$E_T(j3)$	$E_T(j4)$
BMPT	$\geq$ 75 GeV	–	15	15	15	15
CDF	$\geq$ 90 GeV	280	95	55	55	25
D0	$\geq$ 100 GeV	400	35	35	35	20



Baer et al, arXiv:0910.2988

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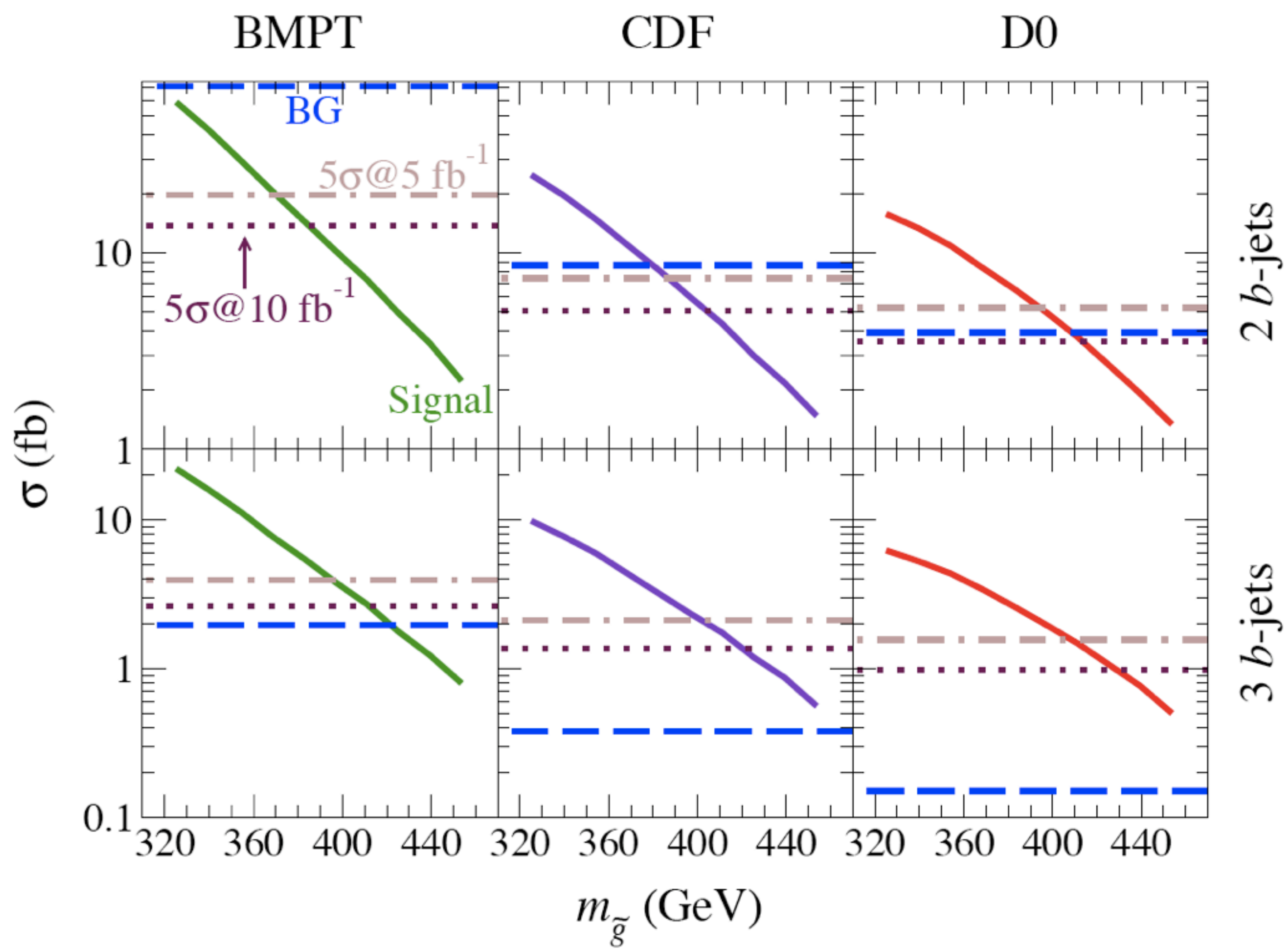

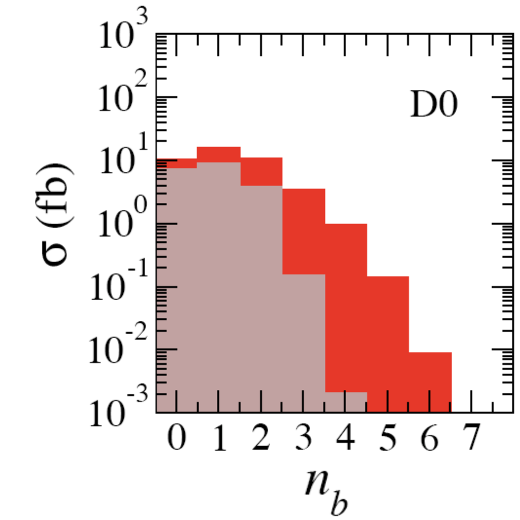

With "D0" cuts and requiring ≥3 b-jets, 5σ discovery reach with 10 fb^{-1} about m(gluino)=430 GeV!

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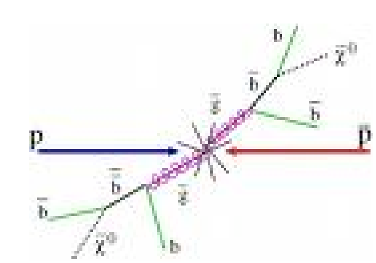
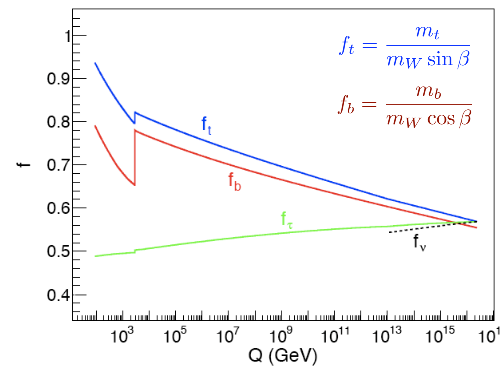


Blazek, Dermisek, Raby, hep-ph/0201081
Auto et al., hep-ph/0302155

Conditions for Yukawa unification (YU)

★ For μ>0, as preferred by b→sγ, Yukawa unification (YU) can only be realized for very particular parameter relations

- $m_{16} \sim 5-15$ TeV,
- $A_0^2 \simeq 2m_{10}^2 \simeq 4m_{16}^2, \quad (A_0 < 0)$
- $m_{1/2} \ll m_{16},$
- $\tan\beta \sim 50.$



$$R = \frac{max(f_t,\ f_b,\ f_\tau)}{min(f_t,\ f_b,\ f_\tau)}$$

★ D-term splitting

$$\begin{aligned} m_Q^2 = m_E^2 = m_U^2 &= m_{16}^2 + M_D^2 \\ m_D^2 = m_L^2 &= m_{16}^2 - 3M_D^2 \\ m_{\tilde\nu_R}^2 &= m_{16}^2 + 5M_D^2 \\ m_{H_{u,d}}^2 &= m_{10}^2 \mp 2M_D^2. \end{aligned}$$

"just-so" Higgs splitting (HS) case

NB: we need $m_{H_u}^2 < m_{H_d}^2$ at $M_{\rm GUT}$, so $M_D^2 > 0$.

- D-term splitting w/o RHN gives R~1.08 (i.e. 8% unification)
- Splitting of only m_H's ("just-so HS") allows for R~1.01
- D-term splitting with RHN gives R~1.04, ...
- ... but if we allow in addition small non-degeneracy of 3rd vs. 1st/2nd generation, we get R~1.02

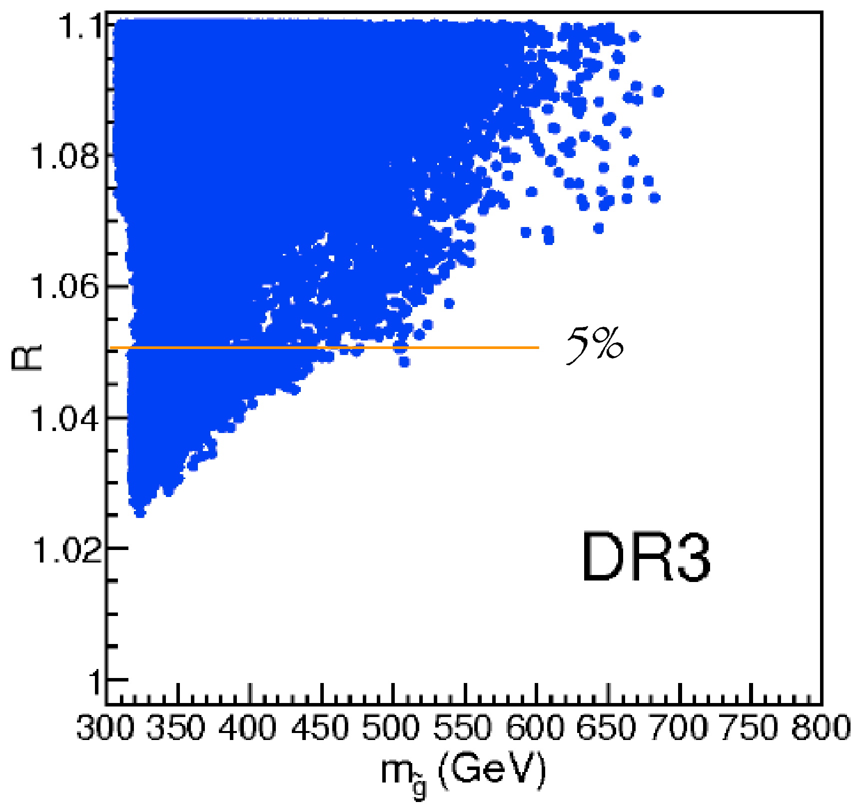
Baer et al., 0908.0134

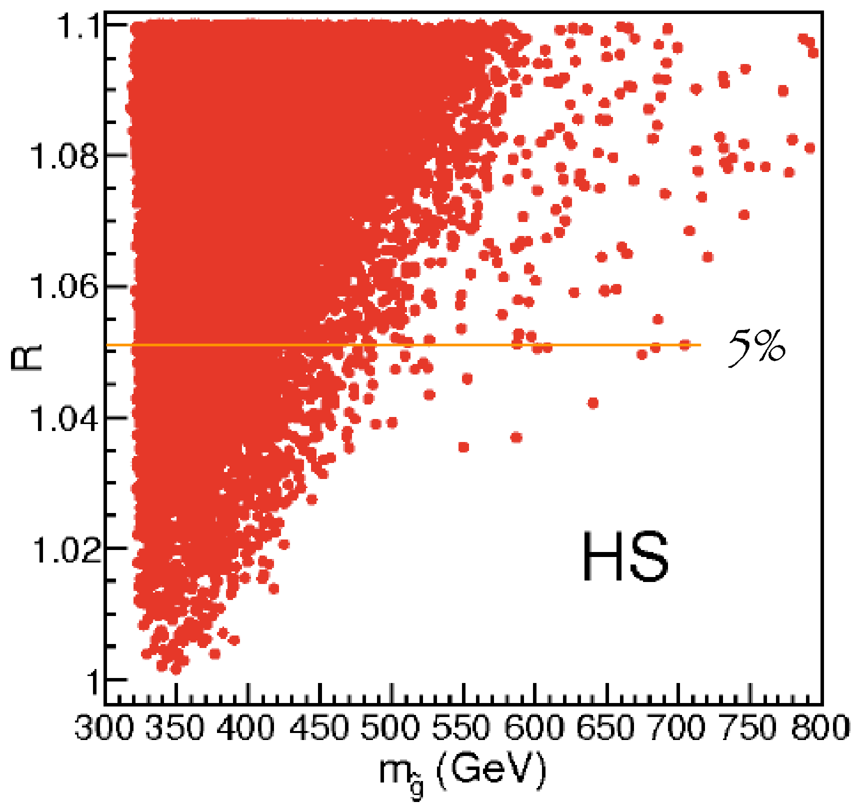
Baer et al, 0801.1831, 0809.0710,
0812.2693, 0908.0134,
0910.2988, 0911.4739.

Typical mass spectra

- 1st/2nd generation scalars in the multi-TeV range (5-15 TeV)
- 3rd gen. scalars, heavy Higgses and higgsinos in the 1-3 TeV range
- light gauginos: LSP ~ 50-80 GeV, gluino ~ 300-500 GeV
- c.f "effective SUSY" by Cohen, Kaplan, Nelson '1996

$$R = \frac{max(f_t,\ f_b,\ f_\tau)}{min(f_t,\ f_b,\ f_\tau)}$$





Points from a MCMC scan for small R